A GEOVISUAL ANALYTICS APPROACH TO SPATIAL AND VISUAL FEATURE ORGANIZATION AND EXPLORATION

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A Geovisual Analytics Approach to Spatial and Visual Feature Organization and Exploration

by

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Abstract

Marine sonar data sets often cover large spatial regions and consist of many hundreds of thousands of sonar pings. The visual representations of the sonar data (echograms) are normally shown as long and narrow ribbons of data. The main challenge with analyzing sonar data using echograms is that the ratio of the length to the height can be very high. As analysts zoom in to show the echogram in sufficient detail, much of the contextual information is lost and horizontal scrolling is necessary to explore and compare the data. In this thesis, a novel approach is proposed that couples a technique for visually clustering slices of the echogram based on visual similarity, with a geovisualization method that shows the spatial location of echogram slices on a virtual globe. A field trial with real-world data analysts was conducted and the results of the field trial illustrate the benefits of this approach.

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Chapter 1

Introduction

1.1 Motivation

Sonar is a technique that can be used to determine the distance and density of underwater objects acoustically [19, 65]. A common application is for a vessel on the ocean surface to transmit acoustic signals to the ocean floor. This sound energy is transmitted, reflected, refracted, and scattered as it interacts with objects below the ocean surface. Some of the sound energy will return to the vessel and can be logged by an acoustic receiver. The amount of time taken to receive the returned acoustic signal provides an indication of the depth of the object that reflected it; the strength of this signal is an indication of the object's mass.

Sonar techniques such as this may be used to measure sub-sea phenomena in disciplines such as fisheries research and physical oceanography [19]. For example, a common use of such acoustic methods is to monitor and analyze fish stocks [21]. Vessels equipped with acoustic gear travel over some region of interest, collecting sonar datasets that may contain hundreds of thousands of sonar pings measured over hundreds of kilometres. Fisheries scientists and environmental managers analyze and explore such sonar data in order to understand the sub-sea environment [53].

Marine sonar data measured in this way can be considered a series of one dimensional data that follow the path of the vessel. That is, the data consists of measurements of reflected energy at depths of the ocean, along a series of latitude and longitude measurements. Analyzing such data in its raw format can be very challenging. A common approach is to generate a visual representation of the data such that the sonar pings and depth are represented along the x- and y- axes respectively, and the strength of the sonar pings are encoded using a colour scale. Such a visual representation is known as an echogram.

The main challenge with analyzing marine sonar data using echograms is that the ratio of the length to the height can be very high. A sonar data set may consist of a large number of sonar pings covering a large geographic region, yet the depth to which the acoustic signals penetrate the ocean may be relatively shallow (see Figure 1.1). Viewing the entire echogram at once for any realistic sonar data set is not feasible. When viewing a portion of the data, it is necessary to scale the echogram such that it will fit on the display. Even on a high-resolution computer display, if too many pings are shown at the same time, the depth of the pings cannot be shown in sufficient detail. That is, the echogram becomes a long but thin ribbon of data. Zooming into a region of interest can allow the analysts to see the details of the data but by doing so they lose the contextual information provided by the entire echogram. Furthermore, making comparisons of data at different locations in the echogram is a difficult task.

Since the echogram is essentially a visual representation of the amalgamation of

Figure 1.1: A sample echogram consisting of 30,000 sonar pings and a depth dimension of 1000 pixels. Note that this is 1/5 of the dataset used in the other examples in this thesis.

the sonar ping data, it does not include any facilities for showing the geographic locations related to the data. A common work-around for this is for analysts to identify key features or important geographic positions in the echogram and manually mark the locations of these features on a map (e.g., using Google Earth). However, as further analysis of the echogram is performed, matching the echogram features with the locations on the map results in added cognitive load for the analysts as they switch their attention between the two representations and attempt to match the data between the two views.

1.2 Approach

The goal of this research is to take a geovisual analytics approach to this problem domain. Geovisual analytics software systems support exploration, analysis, and decision making tasks through the use of interactive visual representations of spatial or spatio-temporal data [3]. Diverse geovisual analytics systems and approaches currently exist, focusing on a variety of different domains [63, 3]. All geovisual analytics systems share the common goal of providing an interactive environment for the purposes of spatial data analysis and decision making.

To address the specific problems of sonar data analysis, a Geospatial-Visual Feature Organization (GVFO) system has been developed. The approach works by first splitting a high dimension echogram into a large number of relatively small *echogram* *slices.* Two different ways of organizing this information are provided to the analysts: the *visual space* clusters the echogram slices based on their visual features, and the *geographic space* represents the path of the measurements of the echogram slices on a map. These two views are shown simultaneously, and are linked as multiple coordinated views [6] such that filtering the data in one view results in the corresponding data being filtered in the other. That is, as the analysts focus the *visual space* on echogram slices that conform to some desired visual features, the locations of the other slices are dimmed in the *geographic space* so that those that remain are highlighted. Similarly, as the analysts zoom the *geographic space* to focus on data in a specific geographic region, the corresponding echogram slices that remain are shown in full brightness in the *visual space*, while all others are dimmed.

This dual mode for filtering the data allow analysts to dynamically control how the data is filtered. Analysts may be interested in both a visual feature of the data and a specific geographic location at the same time. They might start with spatial filtering to reduce the data to be analyzed, then perform visual filtering to focus on some specific features of interest within the echogram slices, followed up by further spatial and visual filtering as necessary to understand the relationships (both based on the sonar data and the locations) among the data. The flexibility of the approach supports knowledge discovery activities, and a more comprehensive analysis of the data across distant geographic ranges than would be possible with the traditional echogram analysis approaches which will be discussed in Chapter 2.

1.3 Research Questions

The key features of the proposed GVFO System developed in this research include echogram slice extraction, visual clustering of echogram slices, geovisualization, and coordinated interaction between the visual space and geographic space. Since the proposed approach moves beyond the existing practice of marine sonar data analysis, it leads to some fundamental research questions, which will be addressed in this thesis:

Does the visual organization of echogram slices enhance the ability of analysts to explore echograms?

The visual organization of echogram slices organizes the slices based on their visual similarities, placing similar echogram slices near one another. The end result is a clustering of the echogram slices that allows the analysts to explore similar echogram slices based on their visual representation of the features of the data. The expectation is that the proposed visual clustering techniques incorporated in the GVFO system may effectively support the analysts in exploring the echograms.

Does the geovisualization of the locations of the echogram slices enhance the ability of analysts to explore echograms?

The geovisual representation of the echogram slices shows the locations of each of the echogram slices on a map. The continuity of the sonar data is lost by partitioning the echogram into smaller echogram slices. The expectation is that the geovisualization of the locations of the echogram slices addresses this problem, and may enhance the ability of the analysts to analyze the sonar data.

Does the coordinated interaction between the visual space and the geographic space enhance the ability of analysts to understand the relation-

ships between the echogram slices?

The primary aim for the coordinated interaction between the visual space and the geographic space is that focusing and filtering operations performed in one space automatically produces the corresponding operations on the appropriate data in the other space. This provides analysts with the freedom to inspect both of the visual features and spatial features of the data at the same time. The expectation is that coordinated interaction may allow analysts to perform their exploratory tasks more effectively and efficiently.

Does the ability to highlight an individual echogram slice and its corresponding geographic location enhance the ability of analysts to explore echograms?

Highlighting an individual echogram slice and its corresponding geographic location allows the analysts to examine the echogram slice further, along with its location. This provides analysts with the ability to inspect the strength of the signal in detail. The expectation is that doing so enhances the ability of the analysts to explore echograms.

Does the ability to merge echogram slices mitigate the risks associated with slicing the echogram over features that might be important?

Slicing an echogram introduces a risk of partitioning it through a specific feature of interest. This is because the process of slicing the echogram into a collection of echogram slices is based on a desired pixel width of the slice. The expectation is that the ability to merge echogram slices mitigates the risks associated with slicing the echogram over features that might be important.

In order to determine the answer to these research questions, field trial evaluations were conducted in this thesis. These field trials measure the potential benefits and drawbacks in a real-world data analysis setting provided by the GVFO system. The value of conducting these field trials is that they have the ability to show how the analysts can incorporate different features of the GVFO system in their existing practice of sonar data analysis.

1.4 Primary Contributions

The first major contribution of this research is the coupling of a technique for visually clustering the echogram slices based on their visual similarity, with a geovisualization method that shows the spatial locations of the echogram slices on a virtual map. Clustering the echogram slices is valuable if an analyst is interested in finding portions of the echogram that are similar (and therefore portions of the sonar data that are similar) but are potentially distant from one another. Alternately, the geovisualization of the echogram slices is valuable if an analyst is interested in the geographic context of the data (i.e., the path the vessel took when measuring the sonar data). Combining these two representations of the same data together allows the analysts to explore the data based on visual features and geographic features simultaneously.

The second major contribution is the coordinated interaction between the two views of the data. The dual mode filtering of the data that is a direct outcome of this coordinated interaction supports both geographic-based exploration that provides visual feature information, and visual feature-based exploration that provides geographic information.

The third major contribution is the inclusion of two features within the GVFO system to mitigate the risk of slicing an echogram through specific features of interest. The first of these is the ability for analysts to merge multiple slices into a larger subset of the echogram. The second of these features is the ability for the analysts to control the width of the echogram slices. Whether wider or narrower echogram slices are appropriate depends on the features of the phenomenon that is being investigated within the sonar data.

1.5 Organization of the Thesis

The remainder of the thesis is structured as follows: Chapter 2 provides an overview of previous research related to this work. Chapter 3 outlines the geovisual analytics approach to sonar data analysis taken in this research, along with the implementation details of the GVFO system. Chapter 4 outlines the details of the field trials conducted to measure the benefits and drawbacks of the system for real-world data analysis activities. The thesis concludes with a summary of the research contributions and an overview of future work in Chapter 5.

Chapter 2

Related Work

This research on geovisual analytics support for the analysis and exploration of sonar data can be informed by research from many different domains. The sections that follow provide an overview of this related work.

2.1 Sonar, Marine Sonar Data, and Sonar Data Visualization

The acronym *sonar* stands for *sound navigation and ranging.* Ocean vessels equipped with sonar equipment may travel over some region of interest, collecting sonar datasets. By sending acoustic signals toward the ocean floor, and then measuring the time it takes for the signals to bounce off of objects (or the ocean floor itself), the distances to these objects can be inferred. Moreover, by measuring the intensity of the reflection, the density of the objects can also be estimated. Collecting such data at a high frequency can allow the sizes of objects to also be determined as the vessel moves along some path.

Such acoustic methods can be used for seabed identification and classification, and can be exploited in many fields, including marine geology, hydrography, marine engineering, environmental sciences, and fisheries [66]. From the fisheries perspective, acoustic methods provide great advantages for studying fish stocks [21] and fish school structures [42]. A careful analysis of the sonar data can be used to identify regions abundant with fish, the sizes of the fish, the depth at which the fish are located, and broader structures of fish school organization, supporting a better understanding of the sub-sea environment [53].

Marine sonar data is often collected over large geographic regions, and may contain hundreds of thousands of sonar pings. The core sonar data includes a timestamp and a series of depths and associated strengths of reflection of the sonar ping. Since GPS can be used in coordination with sonar methods, latitude and longitude measurements are often included with the sonar data.

Viewing and analyzing such raw data is difficult; software tools are often employed to allow analysts to extract the information contained within the data [46]. A common approach is to visualize the data, such that data variables are mapped onto visual dimensions in order to create graphical representations of the data. Such visual representations help to support human cognition on large and/or complex datasets [28], and allow for the perception of unanticipated properties within the data [67].

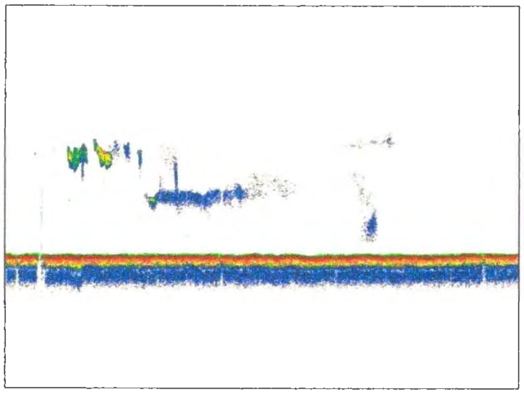
An echogram is a specific method for visually encoding sonar data in a 2D representation, where the x-dimension represents the number of sonar pings in the data, and the y-dimension represents the depth of the sonar ping (which is calculated based on the time differential between when the ping was transmitted and when it was received). The strength of the sonar pings is represented by a rainbow colour scale at a given depth and distance. The rainbow colour scale is not an optimal method for colour encoding since it is not perceptually ordered [9]. As such, it may obscure important features within the data and mislead the analysts. However, it is a common method used in physical science visualization, and experienced analysts can train themselves in its use.

By viewing the colour patterns in the echogram, analysts are shown information about the relative densities, sizes, and locations of objects below the ocean surface. Since the ratio of the length to the height of an echogram is very high, this results in inadequate details being provided for the analysis of the data. If the analysts are interested in viewing a portion of the echogram in sufficient detail, then they can zoom into that region of the echogram (see Figure 2.1). However, doing so results in a loss of context. Alternately, viewing a large portion of the echogram so that contextual information can be seen makes it difficult to see the details.

The echogram does not take into account the geographic locations at which the sonar data were measured, but instead represents the sequence of sonar pings collected. As such, additional cognitive load is required for the analysts to keep track of the spatial locations of the features while they analyze the echogram.

The most common commercial software used by fisheries scientists and analysts for processing sonar data and generating echograms is Echoview [46]. The software also provides tools for navigating and zooming within the echograms, and marking features of interest. Even with such software, the fundamental problem of analyzing sonar data using echograms, and the lack of explicit representation of the geographic features of the data remains: the extreme ratio between the length and the height

(a) An echogram consisting of 30,000 × 1000 pings.



(b) A zoomed in region of the echogram, consisting of 1000 × 1000 ping.

Figure 2.1: An echogram is shown as a long ribbon of data (a). Zooming into a region shows the detail (b).

of the echogram itself. If the analysts view the entire echogram, few details can be seen; if the analysts zoom in to view the details, the contextual information of where the region exists within the entire echogram is lost. Furthermore, comparing features measured at distant locations requires either saving a snapshot of a view of the data, or panning back and forth between different regions of the echogram.

Very little research has been conducted to explore novel approaches for analyzing sonar data. One of the few works is an automated acoustic logging system developed to simultaneously record data from a ship's existing sounder, sonar, and navigation systems. The sonar data is collected in the form of digital images, and combined within a 3D visual representation in order to support the exploration of fish stocks and fish school behaviour [45]. The benefits of this approach are that it provides post processing, editing, and visualization features to map the sonar data to the actual geographic location (see Figure 2.2), and scales the sonar images according to range

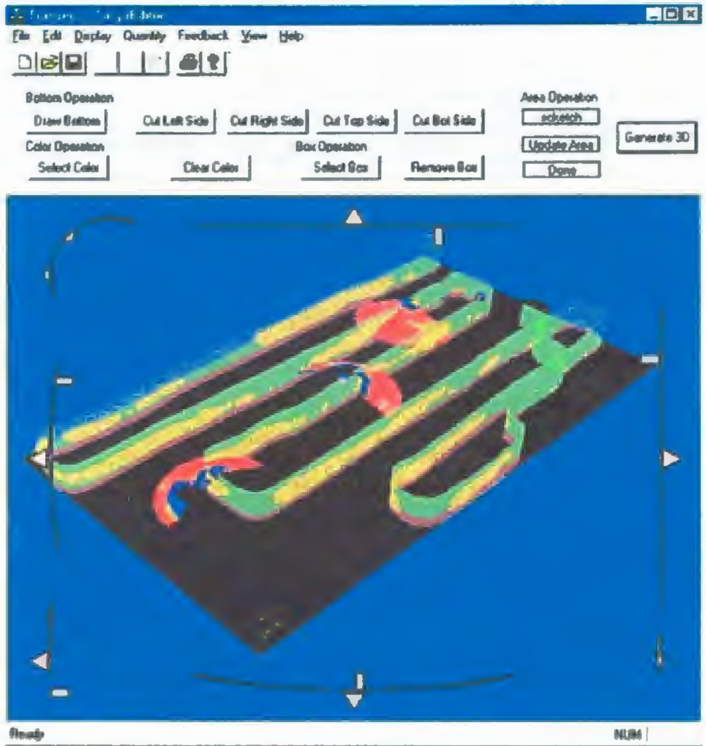


Figure 2.2: Screenshot of the automatic acoustic logging systems and 3D data visualization [44].

settings and tilt angles [44].

In another work, a novel framework was proposed for the analysis and visualization of fish schools in 3D sonar surveys [5]. This framework satisfies specific needs of domain scientists and provides mechanisms for semi-automatic survey reporting, it provides background information on the data characteristics, presents the visual analysis pipeline, and describes how existing visualization methods have to be altered in order to handle specific properties of 3D fishery survey data (see Figure 2.3). However. as with many 3D visualization systems, navigating among the data can be challenging, and making comparisons of distant data is not easy [43].

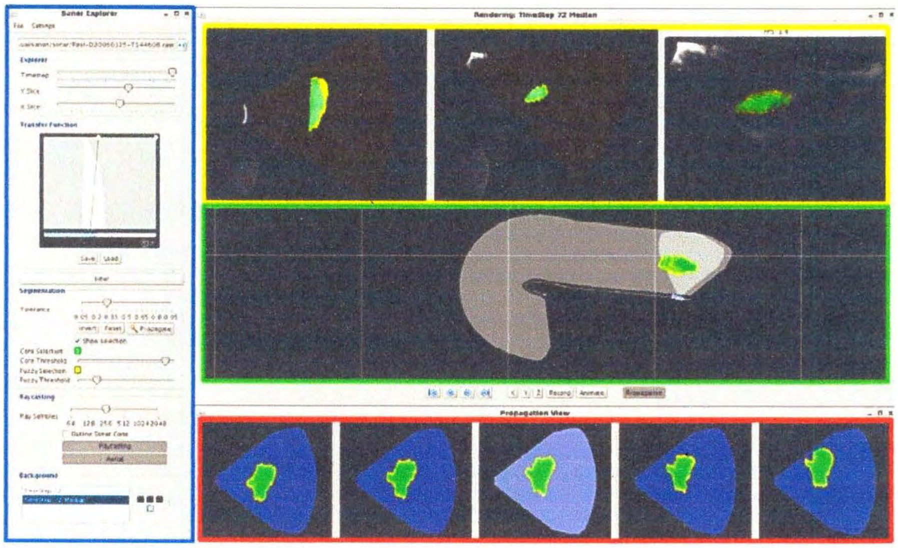


Figure 2.3: Screenshot of the Sonar Explorer application [5].

2.2 Visual Organization of Images

One of the goals in this research is to break a high dimensional echogram into a large number of smaller echogram slices, and then organize these echogram slices in a meaningful way. If an echogram slice is considered an image of the data, then a reasonable approach is to attempt to group visually similar echograms together, and provide a method for navigating among these echogram slices.

Many of the algorithms for image organization do not operate on raw image pixels, but instead extract feature vectors from the images and perform their organization based on these vectors [64]. Features can be extracted based on the colour of the images, the shapes within the images, or using a hybrid approach that combines both colour and shape. Some have suggested that when images are small and shape is imperceivable then colour-based features are most effective [48]. Others have argued that when the shape is apparent in the image, gradient-based feature vectors can be used to effectively capture these aspects of the image [8]. However, it is common for both the visual content of the image and the shape within the image to be important, in which case hybrid approaches may be the most appropriate.

Since colour or gradient information only may not provide the best organization results, a hybrid approach that combines colour and gradient based approaches to describe the visual content of an image [37]. Although there are different such hybrid approaches [18], one that is particularly efficient and effective is colour-gradient correlation, which provides good organizational performance for images [61]. In this approach, a hybrid feature vector of an image is generated with two portions: colour histogram information and gradient direction information. Rather than computing these two portions separately and appending them together, a colour-gradient correlation feature vector is computed by assigning a bin to every possible colour and gradient direction pair, and then summing up the magnitudes of the pixels that have the corresponding colour-gradient direction pair. This feature vector is calculated over every pixel for an input image.

One of the general approaches to visually organizing images for the purposes of this research is similarity-based image browsing [54]. Such approaches organize images based solely on their visual features, allowing for the exploration of the collection even if the user does not have clearly defined goals for what is being sought [23]. While there are a number of different approaches for organizing images within a similarity-based image browsing framework [64, 59], a hierarchical multi-resolution extension to a Self-Organizing Map (SOM) is particularly appealing [60, 62].

A SOM is a special type of artificial neural network that consists of a 2D grid of trainable cells, which are trained using unsupervised learning [33]. The first step in constructing a SOM is to initialize the weight vectors for each cell. From there, a sample vector is selected randomly and the map of weight vectors associated with the cells is searched to find the weightwhich best represents that sample. Since each cell is positioned in a location, it also has neighboring cells (with corresponding weights) that are close to it. The cell that is chosen is updated to become more like the randomly selected sample vector, but to a lesser extent. In addition to this reward, the neighbors of that cell are also rewarded for being able to become more like the chosen sample vector. From this step, the degree to which a cell is updated decreases over time to force convergence. This whole process is then repeated until the feature map stops changing.

A SOM can organize a set of high-dimensional samples, mapping the data to appropriate cells and placing similar data near one another in the 2D grid. As a result, the SOM provides an implicit method for clustering and visualizing high-dimensional data. A SOM is considered a topology-preserving map because there is a topological structure imposed on the trainable cells in the network that preserves neighborhood relations among the input data [12].

While others have explored the use of SOMs within the context of geographic information systems [1, 4], the approach used in this thesis is fundamentally different from those approaches. Rather than clustering the raw data, the approach followed in this thesis is to cluster a geographically continuous subsets of the sonar data (represented by the echogram slices). As noted previously, each echogram slice is represented as a high-dimensional vector; a SOM is used to cluster and organize the associated echogram slices such that those that are visually similar are placed near one another.

One of the fundamental drawbacks of using a SOM to organize a large number of objects is that if each object takes a non-trivial amount of screen space to display, then it is difficult to show the entire set of objects at a sufficiently high resolution. Strong and Gong [60, 62] proposed a solution to automatically generate a hierarchy of progressively smaller resolution SOMs for the organization of images. Starting with a high-resolution SOM that is sufficiently large to map each data object to an unique cell, the resolution is progressively divided in half in both the x and y dimensions. A new SOM is generated at each lower resolution step, where each new cell is the average of the four cells in the higher resolution SOM that it subsumes. The feature vector that is most similar to this cell is taken as its representative image. This process continues in a hierarchical manner until the final low-resolution SOM of size 1×1 is created. For example, starting with a 16×16 SOM, new SOMs of size 8×8, 4×4, 2×2, and 1×1 can progressively be constructed (see Figure 2.4).

This multi-resolution SOM approach to image organization has been used to visually organize and browse within large image collections [60, 62]. In particular, it allows a set of representative images to be shown when there is insufficient space to show the entire collection. To do this, the SOM that most closely matches the image size and screen space constraints is chosen, and only those representative images that have been mapped to this SOM are shown. Zooming facilities allow the user to zoom in to a region of interest. Once sufficient space is available, the next higher resolution SOM is chosen, and more images are shown. Simultaneously, other images are pushed out of the field of view. For this example, starting with an 8×8 SOM, when the user zooms in, the images from the edges get pushed out of the field of view, and space is made for adding in images from the larger 16×16 SOM (see Figure 2.5).

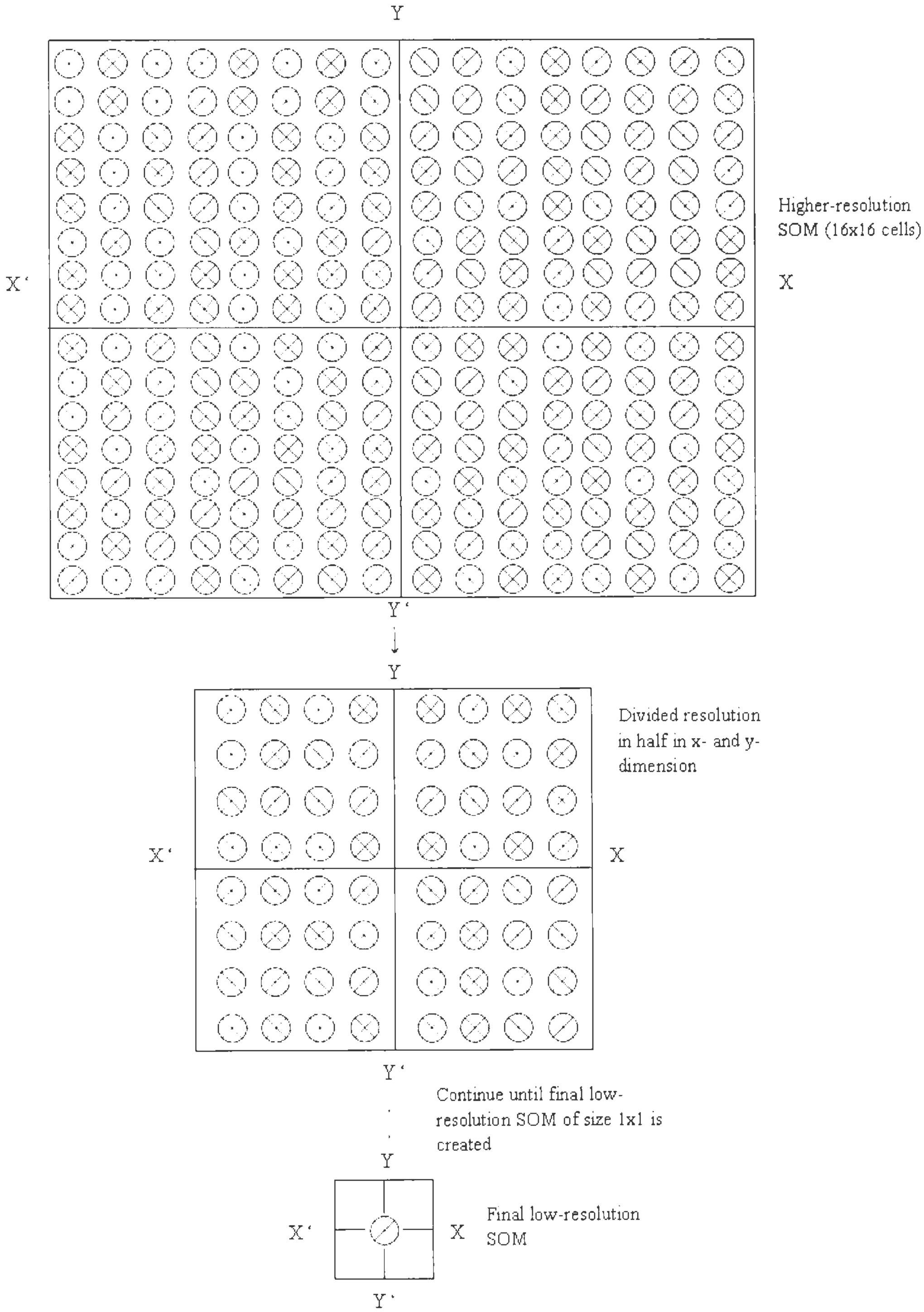


Figure 2.4: Generating a multi-resolution SOM consists of dividing a high-resolution SOM into multiple progressively smaller low-resolution SOMs.

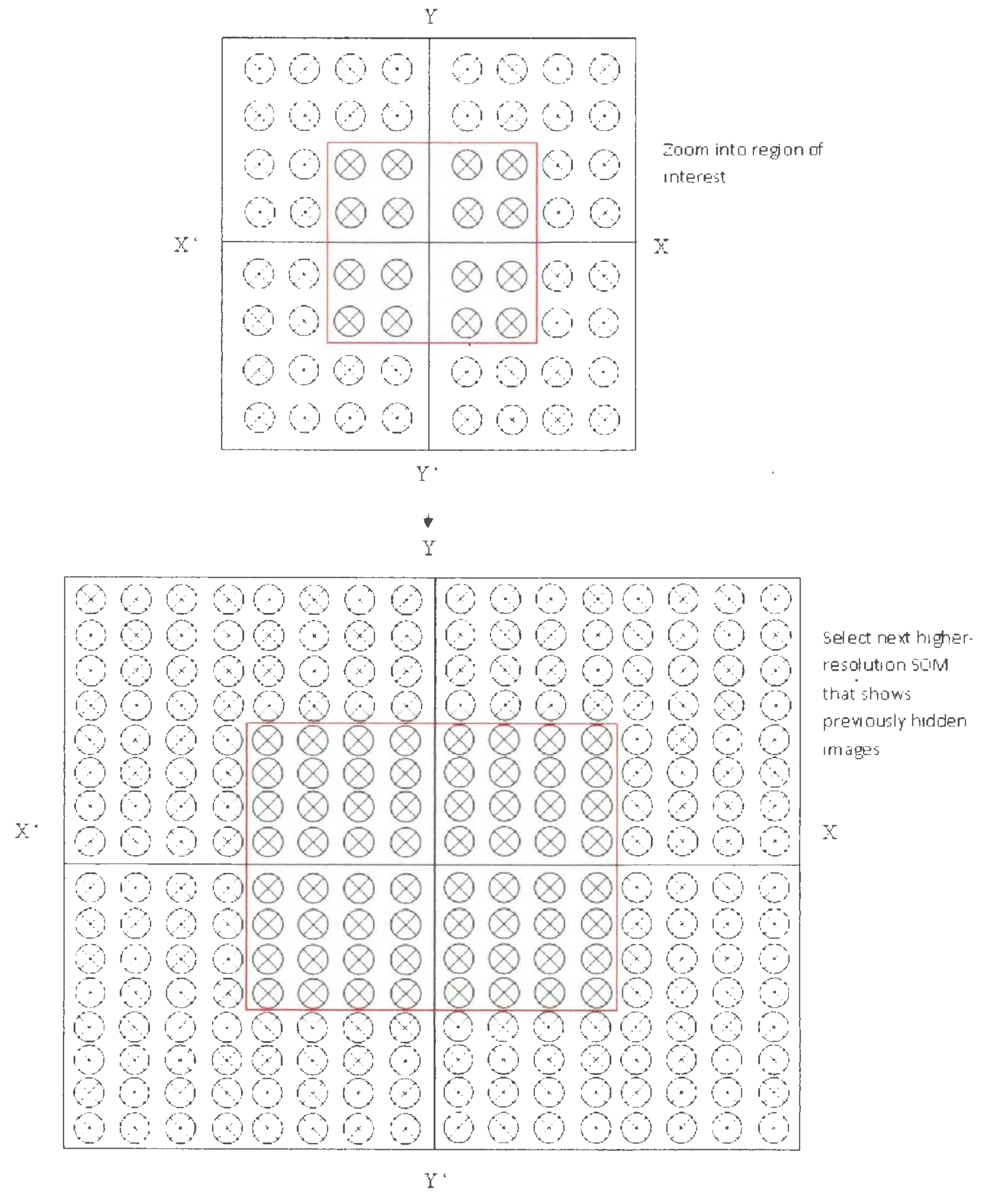


Figure 2.5: Zooming (the red square) results in representative images from the higher resolution SOM being shown.

When using this approach to image organization, at any point in time the number of images shown is much smaller than the available collection. Rather than considering each image in the entire collection, analysts are able to make incremental decisions regarding the importance of a small number of representative images as they zoom into a region of interest [24]. When starting from a set of images organized by a low-level SOM, the zoom operations of the analysts represent approximate decisions. As the analysts zoom deeper into the image collection, images from the higher-resolution SOMs are shown, and their decisions become more precise. Finally, when the highest resolution SOM is shown, and the image collection has been simultaneously filtered and focused through the zoom operations, specific importance decisions on individual images can be made.

This multi-resolution SOM and the associated zooming functionality form the core of the visual organization of the echogram slices within the approach explored in this thesis. The interactive features, along with the quality of the data organization, have been shown to be very useful and easy to use in the context of web image search [27]. The visual representation of sonar data is called echograms (high dimension image) and slicing of these echograms produces a large collection of smaller echogram slices (lower dimension image). Since the visual features of the echogram slices are like the visual features of images, and therefore, the SOM-based organization approach groups similar echogram slices, and therefore similar sonar data. As such similar benefits are expected in the context of organizing the echogram slices and navigating among this data.

2.3 Geovisual Analytics

Information visualization deals with the graphical representations of data that help to reinforce human cognition on the datasets [28]. Information visualization maps data variables onto visual dimensions in order to create graphic representations and provides an interactive way to assist humans in solving problems [49]. Information visualization also provides an ability to comprehend large amounts of data and allows the perception of emergent properties that may not be anticipated. Information visualization reduces the cost of searching for information that uses perceptual attention mechanisms to monitor desired results.

There is no single, generally-suited technique for optimally encoding all types of data. Rather, the way a variable is encoded (that is, what elements are used to produce an effective visual representation of it) depends on the variable itself [31]. The visual variable can be depicted as size, color, shape, location, orientation, texture, and among others.

Interaction is an important element of any information visualization system. The common interaction methods are focusing, brushing, zooming, filtering, details-on-demand, among others. Different visualization system uses different interaction techniques based on the data analysis requirements. These interactions allow users to easily explore the data and gain an understanding of how the elements shown in the different views relate to the same conceptual object.

While the creation of a visual representation may allow the analysts to perceive interesting patterns, this does not automatically mean that they will be able to use this to make their decisions based on the data. In this context, visual analytics is emerging as the science of analytical reasoning that plays a key role in the communication between humans and computers in the decision making process, facilitated by interactive visual interfaces [29]. Visual analytics is more than just visualization; it is an integrated approach combining visualization, human factors, and data analysis [32]. The goal of visual analytics is to synthesize information, and discover the expected and unexpected from massive, dynamic, and often conflicting data [30].

Geovisualization deals with generating visual representations of geospatial data that are layered over top of maps [15]. The goal is to allow users to see the data in relation to landmarks, supporting their understand of the real-world orientation of the data. Geovisualization methods include interactive maps [34], 3D geospatial scenes [38], and time based geographic views [36]. Within these approaches, maps are used to stimulate visual thinking about geospatial patterns, relationships, and trends in a geovisualization environment [41].

Geovisual analytics, then, is the application of visual analytics in the context of geospatial data and geovisualization [55]. It focuses on finding location-related patterns and relationships within a dataset, with the express intent to support data analysis tasks. The goal is to support the decision-making capabilities of the analysts, by allowing them to assimilate complicated spatially oriented situations and reach informed decisions.

Geovisual analytics research has been applied to a number of decision-support domains, including road traffic analysis [22], urban planning [10], route planning [2, 39, 40], changes in fisheries catch data over space and time [25], and fishing vessel movement analysis [16, 17]. The common themes among all of these domains are the representation of data on a map, as well as providing some other domain-specific data to support specific analysis, exploration, and decision-making processes.

TripVista [22] takes advantage of geovisual analytics for exploring and analyzing complex traffic trajectory data providing an ability to investigate microscopic traffic patterns and abnormal behaviours. It uses a spatial view for traffic trajectory information, scatterplots for temporal information of the traffic flows, and parallel coordinates plot for showing multiple properties of the multi-dimensional data. All of these components are linked together as multiple coordinated views using a brushing interaction technique that dynamically updates the different views simultaneously. By using this system analysts are able to make decision about complex traffic data and explore interesting traffic patterns and behaviours.

City'O'Scope [10] was designed to explore and analyze geo-referenced high-dimensional datasets that characterize the attractiveness of cities. By taking advantage of geovisual analytics, it uses a geographic map, list views, a similarity map, and a parallel coordinates plot, with coordinated interaction between these views. Different types of interaction techniques are supported such as selecting (to mark objects), elaborating (to view more details about an object), and zooming (for quick navigations to filter out uninteresting objects). This system allows the analysts to find attractive cities and access their detailed information by using various interaction techniques that promote the users to explore geo-referenced high-dimensional datasets easily.

To prevent mishaps during the winter season, RoadVis [40] applies a geovisual analytics approach for road weather visualization that is able to give a real time visualization solution. It uses a map view to show different bus stations that are in critical conditions, using a parallel coordinates plot for showing the relations between different attributes. This allows analysts to assimilate complex situations to make their decisions about road conditions. Both of these views are linked together, whereby selecting one or several stations on a map view will highlight the other view and vice-versa. By using this system analysts are able to find road conditions (good and bad road condition) easily which allows them to prevent accidents.

Similarly, for making decisions about shipping vessel route choices during harsh weather, a tool named SWIM was developed [39] that combines weather data with data from ship voyages. It uses a geographic map, parallel coordinates plot, and time graph views that are connected as multiple coordinated views. It supports different types of interaction techniques such as selecting (highlight voyage), brushing (focus the ships that travel through the selected area), and zooming (filter out the uninteresting voyages). SWIM is responsible for monitoring fleet and weather development along planned routes and provides support for decisions regarding route choices and to avoid hazards.

GTdiff [25] was designed to support knowledge discovery within fisheries related data that have changed over spatial and temporal ranges. It uses a temporal view, difference view, and geographic view, linked together as multiple coordinated views. The temporal view supports temporal filtering and binning of the data, the difference view provides a visual representation of the difference between each pair of temporal bins, and the geographic view provides a detailed visual representation of selected aspects of the data in the context of their spatial location. It supports different interaction techniques such as selecting, focusing, brushing, panning, and zooming for exploring geospatial and temporal elements of the fisheries data. This system is useful for both exploring the data, and for showing and explaining known phenomena. By using this system experts are able to quickly grasp the meaning of the visual representations, the value of the specific features, and the methods for interactively exploring the data.

All of these systems have used map views that focus on decision making and exploration of the geospatial data for the corresponding domains. Since geospatial data are typically massive and complex, as a consequence of the inherent complexity and heterogeneity of the geographical space, and therefore, all of these systems also have used domain correspondent other views for data exploration from multiple perspectives.

2.4 Multiple Coordinated Views

In order to support the investigation of a single conceptual entity, a multiple coordinated view system uses two or more distinct views that are linked together such that changes in one view are automatically reflected in the other [6]. Viewing the data from multiple perspectives, or using different visualization techniques, is beneficial since each view can reveal different aspects of the data [52]. When used independently, it is up to the users to choose which view to show the data in. When used together, the users can choose which view to consider simply by directing their gaze at the desired view.

By coordinating the interaction such that operations made in one view are automatically reflected in the others, user performance in understanding the data can be improved, and unforeseen relationships can be discovered [6]. Furthermore, showing data from different perspectives assists the users in gaining a more complete understanding of the data, especially if it is high-dimensional [51].

The data explored within geovisual analytics systems is typically large and complex. As such, it is often difficult for analysts to gain insight into the datasets using only one view of the data. Since multiple coordinated views has the ability to show the data from different perspectives, allowing analysts to easily manipulate the data from these different perspectives in order to support their decision-making tasks, many geovisual analytics systems have used this approach to support their data analysis activities [2, 40, 22, 10, 39, 25, 16].

2.5 Discussion

In this chapter, visualization of marine sonar data, the existing practices of the data analysis, and different research domains that correspond with sonar data exploration were briefly reviewed. An overview of some of the different approaches were surveyed for sonar data exploration. In particular, a number of different research domains were discussed that are relevant to this research: sonar data visualization, visual organization of images, geovisual analytics, and multiple coordinated views.

From the literature review on sonar data visualization, a number of difficulties were discussed. Since viewing and analyzing raw sonar data is difficult, Echoview software has been used to process sonar data and visualize the data as echograms. Analyzing sonar data using echograms also suffers from the extreme ratio between the length and the height of the echogram itself.

A number of different approaches were discussed for organizing images within a similarity-based image browsing framework. A particularly appealing approach that was explored in detail was the use of a SOM to organize the images. Although a SOM provides an intuitive way to organize images, it has a limitation of not being able to show the entire set of images at a sufficiently high resolution within a non-trivial amount of screen space. The solution of this problem is the multi-resolution SOM.

The visual representation of sonar data (echograms) does not include any facilities for showing geographic locations related to the data. As such analysts manually mark the locations of the echogram features on a map and match the interesting features (echograms) with the locations resulting in additional cognitive load when analyzing the data. Geovisual analytics approaches focus on finding spatial patterns and relationships within the datasets to support analysis tasks. As such, it is beneficial to incorporate geovisual analytics approaches for the exploration of sonar data.

Since geospatial data are typically massive and complex, it is difficult to find the relationships among the data using only one view. Multiple coordinated views offer many advantages for exploring unforeseen relationships among data by using two or more distinct views. Most of the geovisual analytics systems from different decision-support domains take the advantage of multiple coordinated views to explore the domain specific data. As such, using of multiple coordinated views is a potentially useful approach for sonar data analysis tasks.

Chapter 3

Approach

3.1 Motivation

It is common for marine sonar datasets to be large, both in the number of sonar pings as well as the geographic distance covered. As a result, the corresponding echograms may be hundreds of thousands of pixels wide. The main challenge with analyzing marine sonar data using echograms is that the ratio of the length to the height can be very high. The alternatives for viewing the data are to either view the entire echogram and not be able to see any detail, or zoom in so that detail can be seen, but then lose the contextual information provided by the full echogram.

Rather than viewing echograms in such a way, an approach can be taken that partitions a high dimension echograms to produce a large number of lower dimension echogram slices, and therefore, the ratio of the length to the height of the echogram slices can not be very high. Since echogram slices are the visual representation of sonar data, organization of the echogram slices based on their visual similarities forms a cluster that allows the analysts to identify features of interest in the echogram slices as they analyze the data.

While visual clustering can allow an analyst to easily identify interesting features within the echogram slices, what is lost is the continuity of the echogram.There is also a need to illustrate the spatial aspects of the sonar data that are not encoded in the echogram.

Moreover, in order to support data exploration based on the visual features and geographic features, a technique can be used that shows both of the features simultaneously. This simultaneous exploration allows the analysts to analyze the data easily that does not require additional cognitive load to keep track of both the features of data.

In this chapter, the Geospatial-Visual Feature Organization (GVFO) system is described in detail. Where necessary, illustrative examples are provided to depict how the approach works.

3.2 GVFO System

The GVFO system for supporting the analysis of marine sonar data consists of components that perform echogram slice extraction, display the data in both a visual space and a geographic space, and coordinate the interaction between these two views in order to support data exploration. Below, the details of the entire system are outlined. An overview of the GVFO system is illustrated in Figure 3.1. Different types of colour encoding are used to illustrate the approach: purple represents sonar data collection, high dimension echogram formation, and echogram slice formation steps; blue repre-

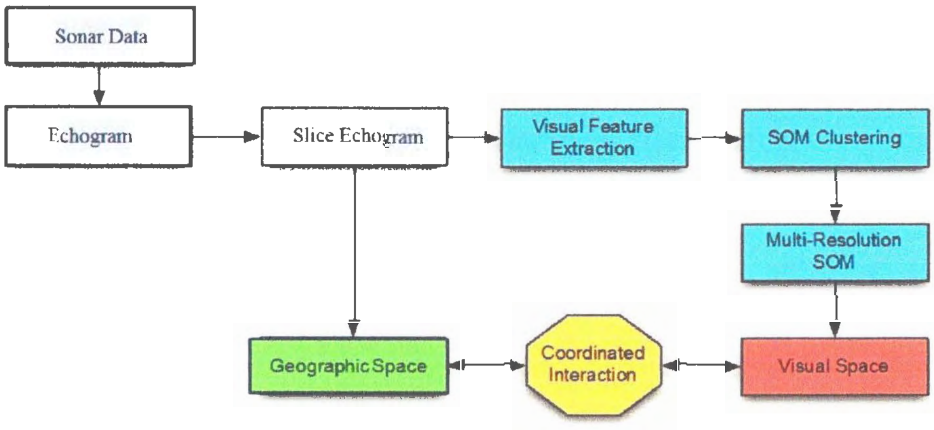


Figure 3.1: Overview of the approach.

sents visual feature extraction, and the organization of echogram slices based on their visual features steps; green represents geographic space that shows geographic locations of echogram slices; red represents visual space that shows clustering of echogram slices; yellow represents coordinated interaction between visual space and geographic space. The portion of work of this thesis that is based on Strong's [60, 61, 62] work is represented by the blue colour.

3.2.1 Echogram Slice Extraction

The first step is to pre-process the echogram such that an analyst can more easily perceive patterns within the sonar data. The goal is to slice a large echogram width-wise into a large number of smaller *echogram slices*, which can then be used to simultaneously represent the data based on common visual features (within the visual space) and based on the locations of these visual features (within the geographic space).

In the prototype system, a simple approach is taken for this task, whereby the echogram is divided evenly into the echogram slices. For example, a $300,000 \times 1,000$ pixel echogram may be partitioned into a set of 300 individual 1000×1000 pixel echogram slices. Since the ratio of the width to the height is more balanced for these lower-dimension echogram slices, they can more readily be shown to the analyst in high-resolution without the need for horizontal scrolling as is common with the full echogram. For each echogram slice, the geographic location of the centre point is also determined.

In this research, the size of each echogram slice was chosen as 1000×1000 pixels. One of the problems with this approach is that the slicing technique may divide an interesting visual feature among multiple echogram slices. Dynamic control of the width of the echogram slices can allow the analysts to mitigate this problem. For example, a 300000×1000 pixels echogram may be partitioned into a set of 150 individual 2000×1000 pixels echogram slices or partitioned into a set of 200 individual 1500×1000 pixels echogram slices based on the analysts' needs.

More complex approaches may also be possible, such as using computer vision techniques to determine potentially interesting features, and avoiding dividing these when determining the width of each echogram slice. While such an approach is certainly feasible, it introduces the problem of variably sized echogram slices which adds another level of complexity to the system. As such, a simple solution is opted for the slicing of the echogram in order to focus on the study of the overall approach.

3.2.2 Visual Space

After generating a collection of numerous smaller echogram slices, the problem then is how to organize these in a logical manner. In order to promote analysis and exploration of the data, a useful approach would be to group echogram slices that contain visually similar features. Doing so could allow an analyst to identify a feature of interest among the collection, focusing on those echogram slices with similar features. However, one of the fundamental problems with the approach of breaking a large echogram into many smaller echogram slices is that there will likely not be sufficient screen space to show all of the echogram slices at once in sufficient detail.For this reason, the visual organization of the echogram slices should not only group related echogram slices, but also aggregate them in a flexible manner that allows for subsequent expansion during the analysis tasks.

The method employed in this work for such a visual organization of the echogram slices is to use a multi-resolution SOM similar to that proposed by [60, 62], previously outlined in detail in Section 2.2. To use this approach, the echogram slices must be converted into high dimensional feature vectors that can be used to train the bottom-level SOM. For this purpose, the colour-gradient correlation method is used [37], as discussed in Section 2.2.

The multi-level nature of the approach produces a hierarchy of SOMs at progressively lower resolutions. Not all of the echogram slices are mapped to these higher-level but lower-resolution SOMs. Instead, with each step up in the generation of the multi-level SOM, the average feature vector of the merged cells is calculated, and the feature vector that is most similar to this average is chosen to display along with its corresponding echogram slice.

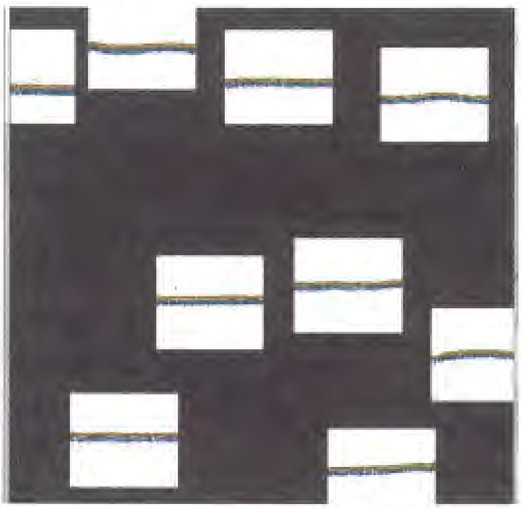
This multi-resolution SOM can be mapped to an intuitive and interactive organization of the echogram slices base on their visual similarity. Continuing to follow the approach by [60, 62], a zoomable *visual space* is provided to the analyst. Due to the aforementioned problem of not being able to show all of the echogram slices at a sufficiently high resolution, a high-level of the multi-resolution SOM is used to visually organize a representative subset of the echogram slices. The echogram slices that are shown can be considered surrogates of the implicit clustering of the SOM.

The analyst can visually browse these echogram slices, seeking features of interest. When a particular region of the visual space is identified as worthy of further exploration, the analyst can zoom into this region. Doing so pushes those echogram slices that are distant from the focal point of the zoom out of the field of view, and creates more space between the echogram slices near the focal point. Once sufficient space is available, the multi-resolution SOM is traversed to a lower level, and the echogram slices that are representative of this higher-resolution space are then shown. This zoom operation continues to show more and more echogram slices until the bottom level of the SOM is reached. At that time, further zooming increases the resolution of the echogram slices themselves (see Figure 3.2).

This zooming operation also operates in the reverse direction (zoom out), aggregating the echogram slices when a broader overview of the data is desired. Echogram slices that were pushed out of the field of view during a zoom in operation are pulled back into view by the zoom out operation. The zoom out operation also selects a higher-level, low resolution SOM and shows only the most representative echogram slices, and hiding the rest.

(a) Region (the red square) of interesting visual features of the echogram slices

(b) Zooming into interested region selects higher-resolution SOM that creates more space to display hidden echogram slices



(c) Further zooming (the red square) increases the resolution of the echogram slices

Figure 3.2: Exploration of echogram slices using multi-resolution SOM. Analysts are interested in a region (the red square)identified as worthy of exploration (a), zooming into that region selects higher-resolution SOM that creates more space to display hidden echogram slices that were not shown before (b), and further and further zooming increases the resolution of the echogram slices to examine those in more detail (c). The red box is not part of the interface, but instead is illustrating the zoom region.

The analyst may pan within the visual space, moving the focal point of the display as necessary to focus the zoom operations on the desired region of interest. By using this panning operation, they can also switch back to their previous region of interest.

3.2.3 Geographic Space

While the visual clustering of the echogram slices described in the previous section can allow an analyst to visually identify and explore interesting features within the data, what is lost by partitioning the echogram into slices is the continuity of the sonar data. To address this, and to further enhance the understanding and analysis of the spatial aspects of the data, a geovisual representation is provided to show the locations of each of the echogram slices on a virtual globe. This *geographic space* is displayed independently of the visual space, but supports coordinated interaction as will be explained in the section that follows.

Different types of glyphs can be used to represent the locations of each echogram slices such as cube, cone, cylinder, sphere, triangle, and among others. Rather than simple marks, directional glyphs (triangles) are used to represent the location of each echogram slice, as well as the direction in which the source echogram was measured. The glyphs, together with cubic Hermite splines [35] that produce curved lines connecting the glyphs, provide an obvious and clear depiction of the path of the sonar data (see Figure 3.3). This is especially true in regions of congestion where the path may criss-cross; in these locations the directionality of the glyphs make it clear which belong to which path, and the curved lines make it easier for the human eye to follow the path [67]. In Figure 3.3, an artifact is introduced because of the curved lines that

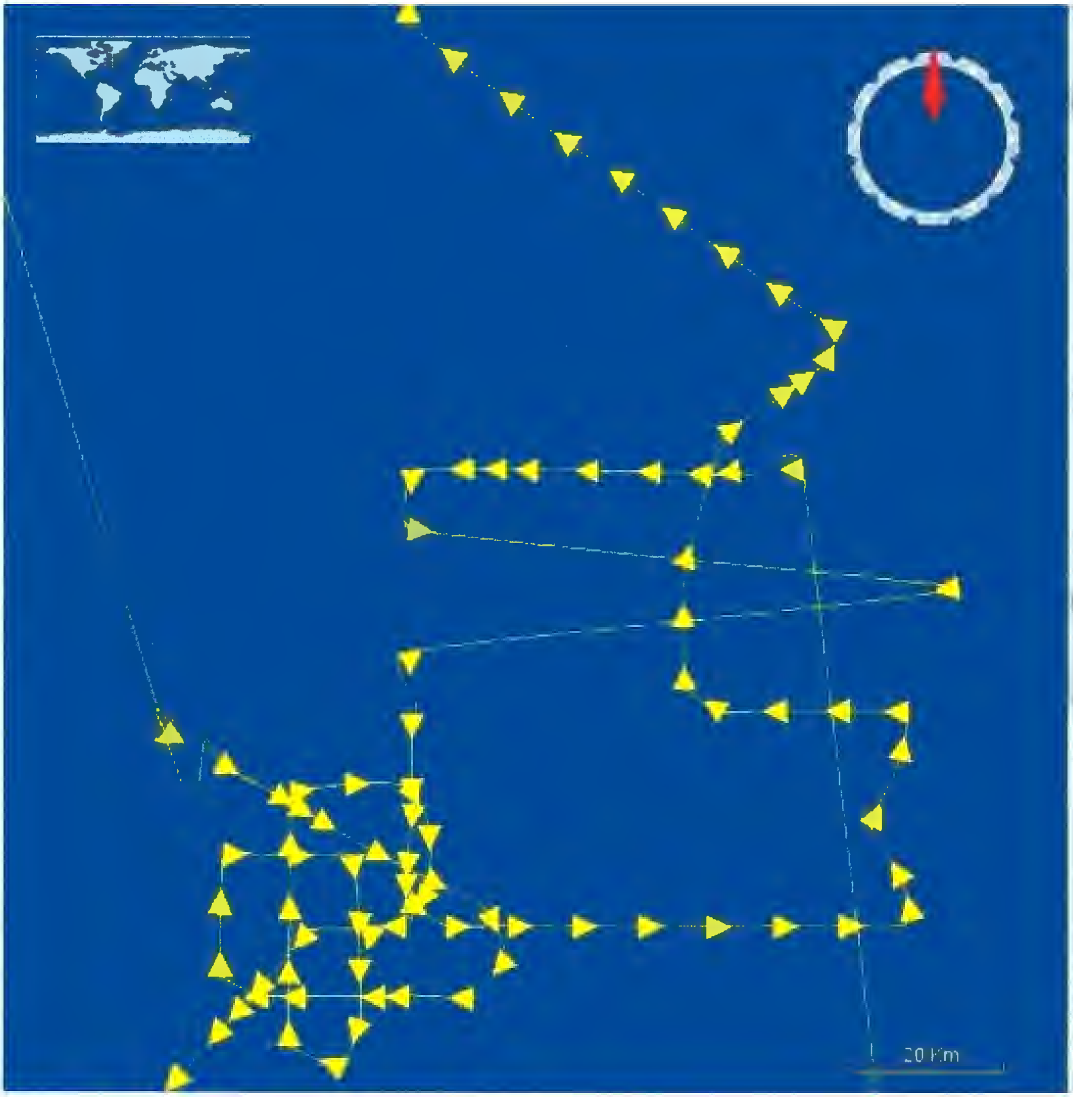


Figure 3.3: Geographic representation of the echogram slices.

is a drawback of using cubic Hermite splines.

An obvious interaction mechanism when representing the locations of the echogram slices on a virtual globe is to support pan and zoom operations. As the analyst zooms into an area of interest, the geographic contexts of the data are shown in more detail and regions distant from the focal point are pushed out of the field of view. Panning can be used to change the region of focus as necessary. This interaction mechanism follows the standard practice with interactive maps.

As noted previously, slicing the echogram may result in particular features of interest being divided between multiple slices. To support the analyst in understanding and further analyzing these features, a feature for merging echogram slices is provided within the geographic space (as illustrated in Figure 3.4). By selecting the start and end glyphs of some path of interest, the corresponding echogram slices are merged together within the visual space. The start and end points are coloured green in the geographic space to allow the analysts to see the geographic extent of the merged echogram slices. This larger echogram slice can then be examined in detail as required by the analyst.

3.2.4 Coordinated Interaction

In order to enhance the connection between the visual space and the geographic space outlined in the previous sections, these interface elements operate as multiple coordinated views [6]. That is, the focusing and filtering operations in one space automatically produces corresponding operations on the appropriate data in the other space. As a result, when an analyst selects an echogram slice in the visual space, its corresponding glyph in the geographic space is highlighted. Similarly, when an analyst selects a glyph in the geographic space, its corresponding echogram slice in the visual space is highlighted.

This coordination also holds for the pan and zoom operations on both the visual and geographic spaces. These operations not only show the data near the focal point in more detail, but also filter data that is distant from the focal point and therefore out

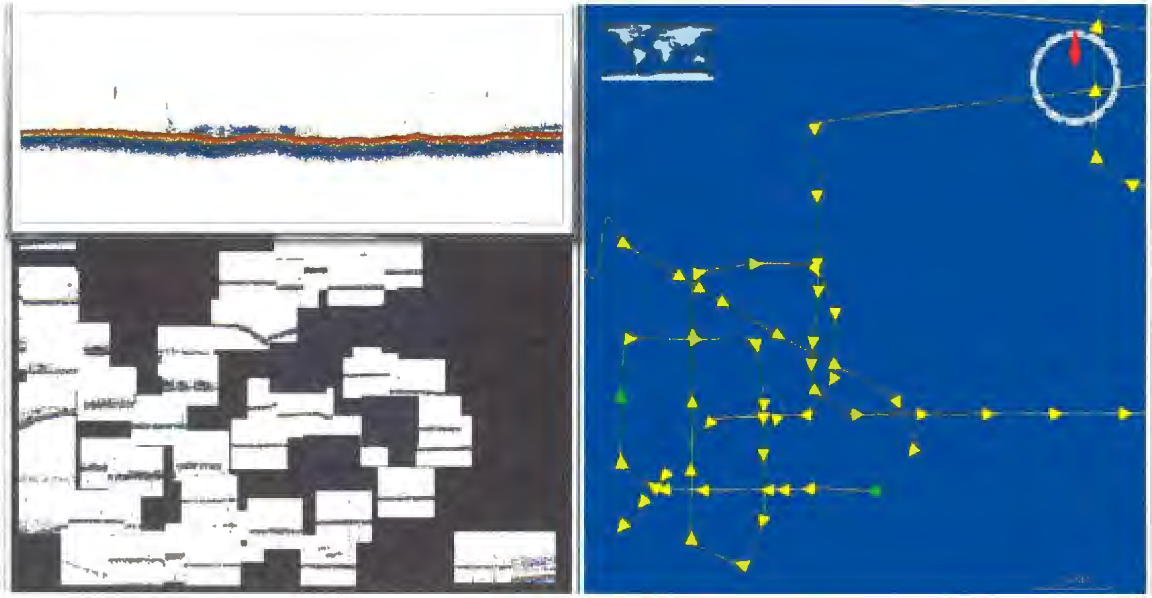
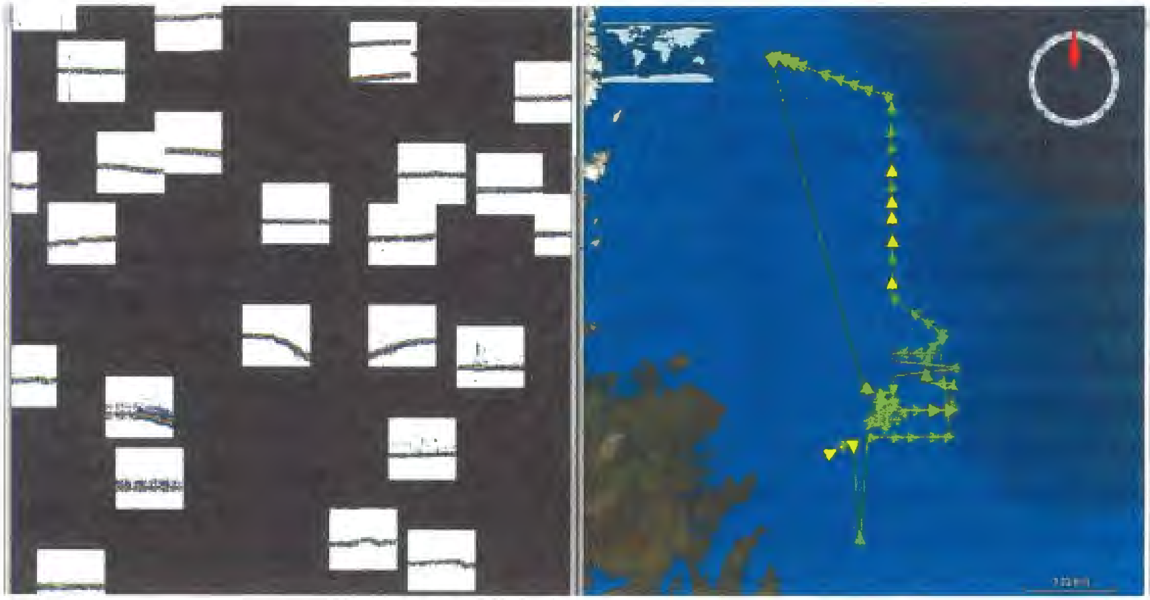


Figure 3.4: Merged slices (left) after selecting the beginning and end point within the geographic space (right).

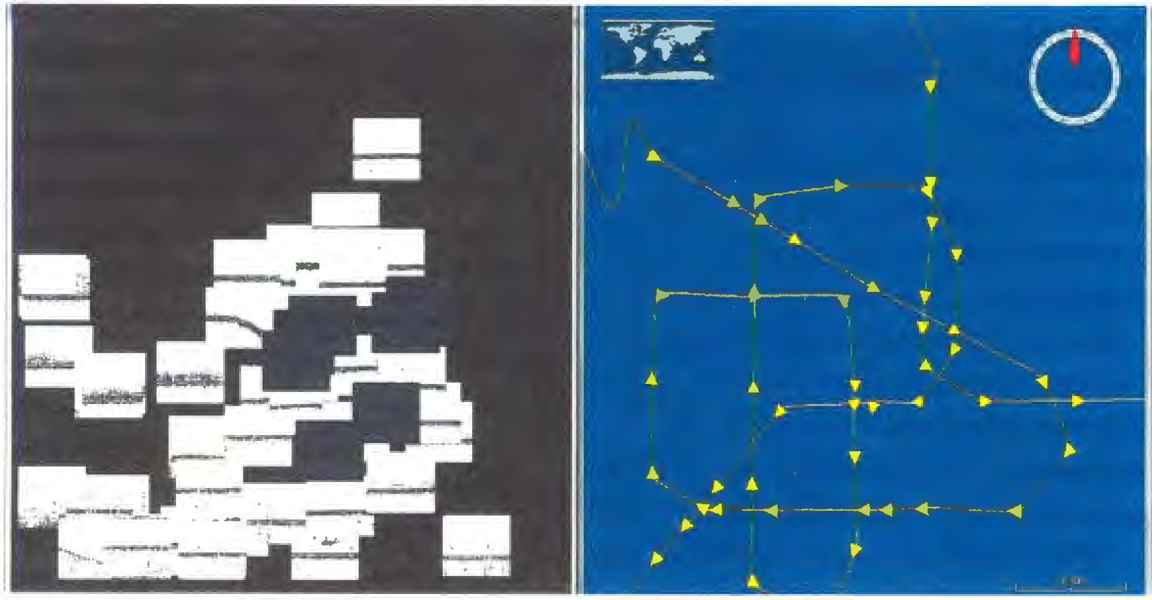
of the field of view. When this happens as a result of the analyst's zoom operations within either of the views, the corresponding data objects (echogram slices or glyphs) are dimmed in the other view. Doing so allows the analyst to readily determine the results of their actions across both views (see Figure 3.5).

3.2.5 Example

Consider a situation where a marine sonar data analyst wishes to explore and analyze a data set consisting of 151,836 sonar pings covering a linear geographic range of 1040 km. The traditional approach to analyzing such data would be to show the entire echogram in software such as Echoview, zoom in and out on features of interest, and pan back and forth over the echogram. However, as noted previously, this approach makes it difficult to view similar features at distant locations in the echogram slice, and requires the analyst to manage the geographic locations of the echogram data in



(a) Zooming into the visual space



(b) Zooming into the geographic space

Figure 3.5: Zooming into a region of interest in the visual space (left) results in the locations of the echogram slices that are outside of the viewport to be dimmed in the geographic space (right) (a), Zooming into a region of interest in the geographic space (right), the corresponding echogram slices that are located outside of the viewport are dimmed in the visual space (left) (b).

a separate software system. As such, the ability to analyze the data is limited and requires a great deal of cognitive effort on behalf of the analyst.

With GVFO, this echogram can be sliced into 152 individual 1000 $\times$ 1000 pixels echogram slices. These are organized based on similarity of their visual features in a zoomable visual space. Simultaneously, the locations of these echogram slices are represented within a zoomable geographic space. By default, both spaces are zoomed out to show an overview of the echogram slices and the entire geographic range of the data (see Figure 3.6).

The analysts may wish to explore the echogram slices in detail, seeking some interesting pattern within the data. As the analysts zoom within a visual region of interest, uninteresting echogram slices are pushed out of the field of view, and the corresponding glyphs in the geographic space are dimmed (see Figure 3.7). Simultaneously, as more space is created between the echogram slices, previously hidden slices are inserted into the view.

Alternately, the analysts may be interested in a geographic subset of the data, where they know a particular species of fish is normally present. Zooming into this geographic region not only filters the data within the geographic space, but also dims the echogram slices that are outside of this geographic range (see Figure 3.8).

After this spatial zooming, the analysts may be interested in comparing similar echogram slices that are grouped together within the visual space. Performing zooming within the visual space follows the same pattern as described above, moving echogram slices outside of the field of view, dimming their corresponding glyphs in the geographic view, and showing previously hidden echogram slices as more space is created. Further zooming once all of the hidden echogram slices are shown results in

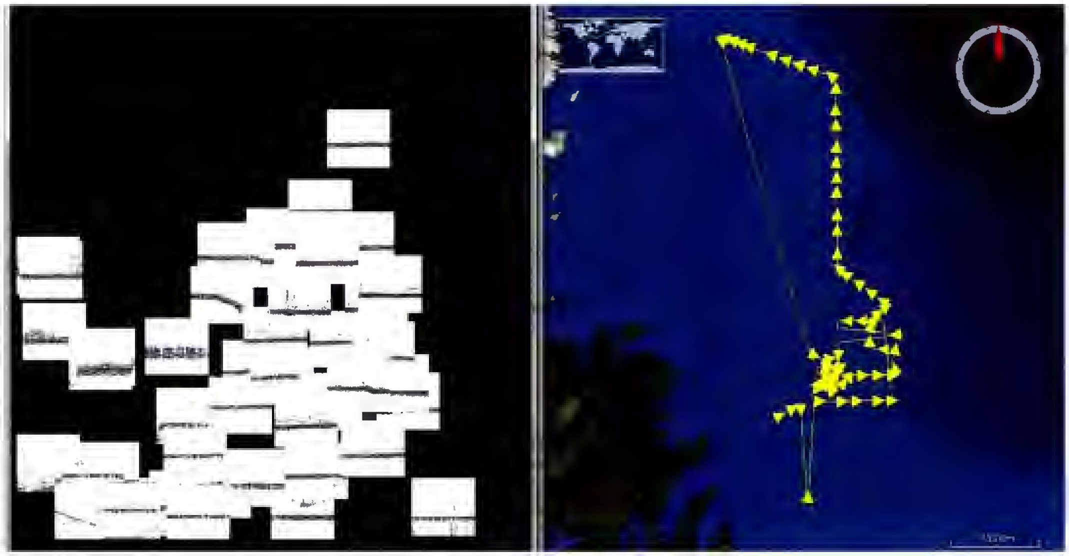


Figure 3.6: Initially, the echogram slices are clustered in the visual space (left), and their locations are shown in the geographic space (right).

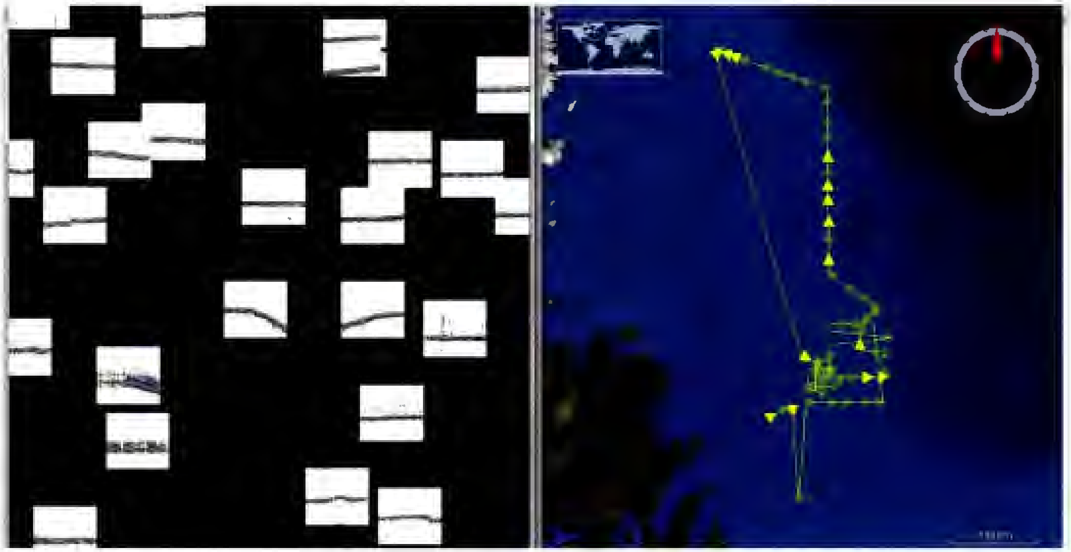


Figure 3.7: Zooming into a region of interest in the visual space (left) results in the locations of the echogram slices that are outside of the viewport to be dimmed in the geographic space (right).

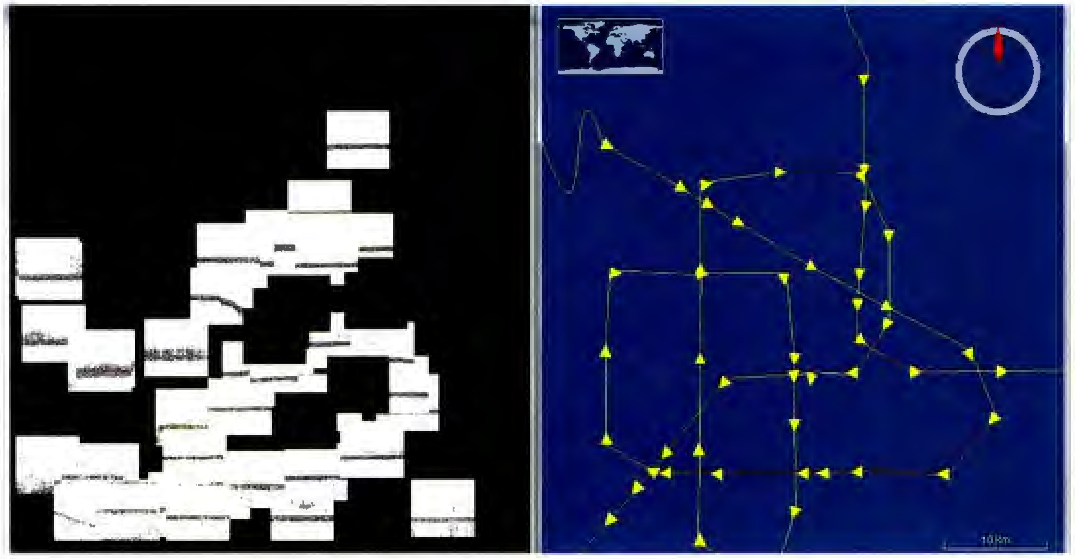


Figure 3.8: As the analyst zooms in within the geographic space (right), the corresponding echogram slices that are located outside of the viewport are dimmed in the visual space (left).

increasing the resolution of the echogram slices (see Figure 3.9). This process allows the analysts to compare and analyze visually similar echogram slices, even though they may be from distant locations within the data.

If at any point in time the analysts identify a particular echogram slice that they wish to examine further, they can click on it to highlight it. Doing so expands the echogram slice to fill much of the visual space. At the same time, its corresponding glyph in the geographic space is highlighted (see Figure 3.10). The result is the same if the analysts also choose the glyph from within the geographic space instead of the echogram slice from the visual space.

Should the analysts identify a region where it appears that the echogram slices have divided the data over some interesting feature, they can patch these back together to show a larger echogram slice. This is done from the geographic view by

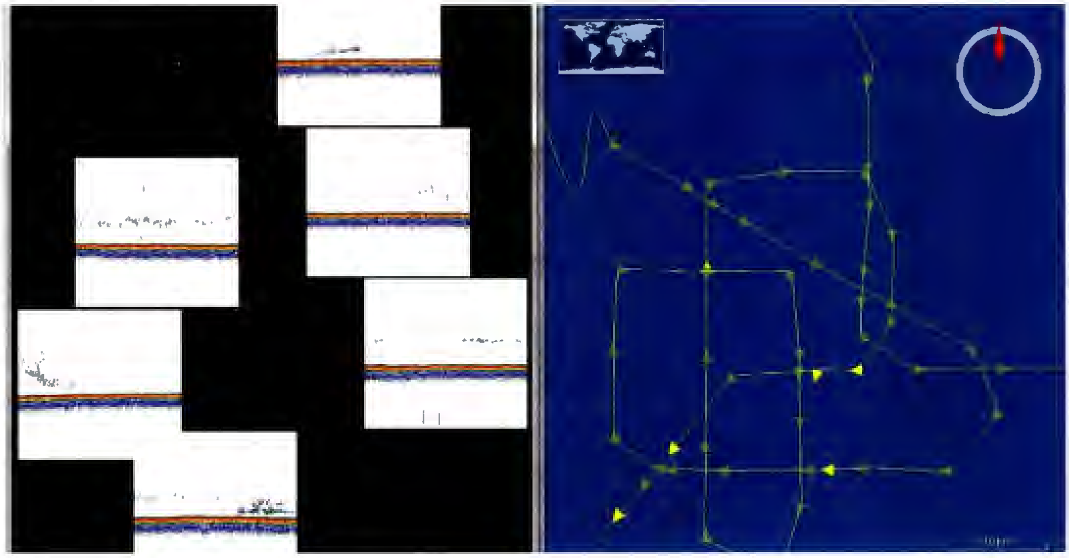


Figure 3.9: Zooming deep within the visual space (left) shows a small number of visually similar echogram slices. Viewing the geographic space (right) allows the analysts to determine the geographic relationship among these echogram slices.

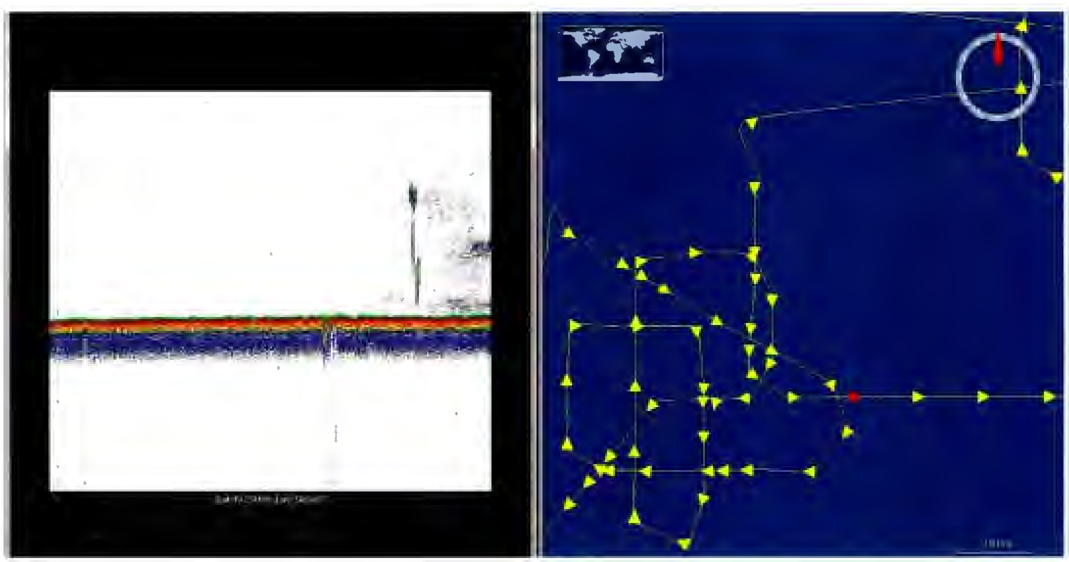


Figure 3.10: Selecting a specific echogram slice (or glyph) highlights the corresponding object in the other view.

holding down the control key while selecting the start and end points of a path of the echogram. These end-points are highlighted, and the collection of their corresponding echogram slices are stitched back together and shown in the visual space (see Figure 3.11).

The dual filtering mode, with coordinated interaction between the visual and geographic zooming, and the ability to highlight individual echogram slices and stitch multiple echogram slices back together provides a powerful tool to support the analysis of sonar data. The analyst is provided with a great deal of control over how the data can be explored. After performing geographic and visual zooming operations, they can readily go back to perform further fine-tuning of the geographic extent and further panning and zooming within the visual space to focus on particular features of the sonar data that are of interest. Individual echogram slices can be examined in detail, and if the analysts think there might be some interesting features at the boundaries between the echogram slices, these can be stitched back together and investigated.

The flexibility of interactively filtering and exploring the echogram supports a more focused analysis of the sonar data across the entire range of the data than what would be possible with traditional approaches. In particular, the ability to examine visually similar echogram slices that may be from geographically distant locations is something that is particularly difficult with traditional echograms, but relatively simple with the GVFO system.

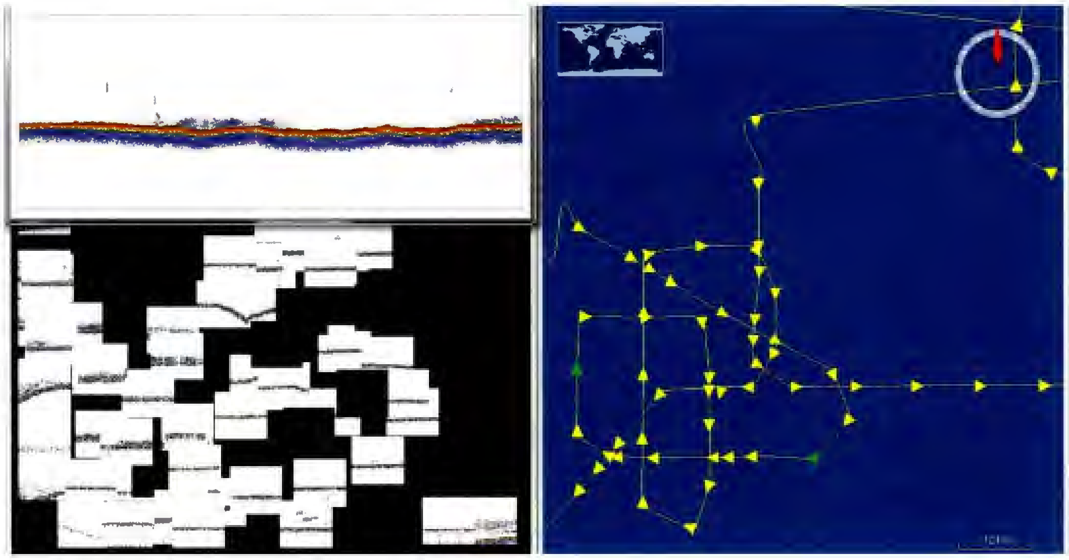


Figure 3.11: Merged slices (right) after selecting the beginning and end point within the geographic space (left).

3.3 GVFO System Implementation

3.3.1 System Design

The GVFO system has been built in order to study a geovisual analytics approach for the exploration of sonar data. The core of the system was built in the early stage of this research and updated continuously as the research progressed. It couples a technique for visually clustering slices of the echogram based on visual similarity, with a geovisualization method that shows the spatial location of echogram slices on a virtual globe.

3.3.2 Platform

The GVFO system was developed using the Java programming language [58], and NASA World Wind [47] as the virtual globe. The core software for the visual space (the multi-resolution SOM) and the geographic space (NASA World Wind) were both written in Java. As such it was relatively easy to modify and extend these systems to implement the desired functionality of the GVFO system. In addition, all new components were implemented in Java.

The reason for using NASA World Wind is that it offers many advantage over other virtual globes such as Google Earth [26]. In Google Earth the resolution of images is uneven whereas NASA World Wind provides better quality satellite imagery [7]. In NASA World Wind the images are public domain, thus educational use of these images does not require copyright permission. Another key advantage of NASA World Wind is that the source code is available allowing for relatively easy implementation of custom visual encoding of the geographic data and interaction mechanisms. As such, to build the GVFO system NASA World Wind has been used as the virtual globe to represent the geographic locations of the echogram slices.

3.3.3 System Architecture

The architecture of the GVFO system is shown in Figure 3.12. Different types of colour encoding are used to illustrate the architecture of the GVFO system:blue represents the steps of the exportation of high dimension echogram; light green represents the formation of echogram slices from high dimension echogram, dark blue represents the steps of echogram slices organization based on their visual features using multi-resolution SOM. The *visual space* and *geographic space* is represented by light red and light orange respectively. The general workflow of the system is outlined below:

At the first step, marine sonar data is collected and visualized as an echogram

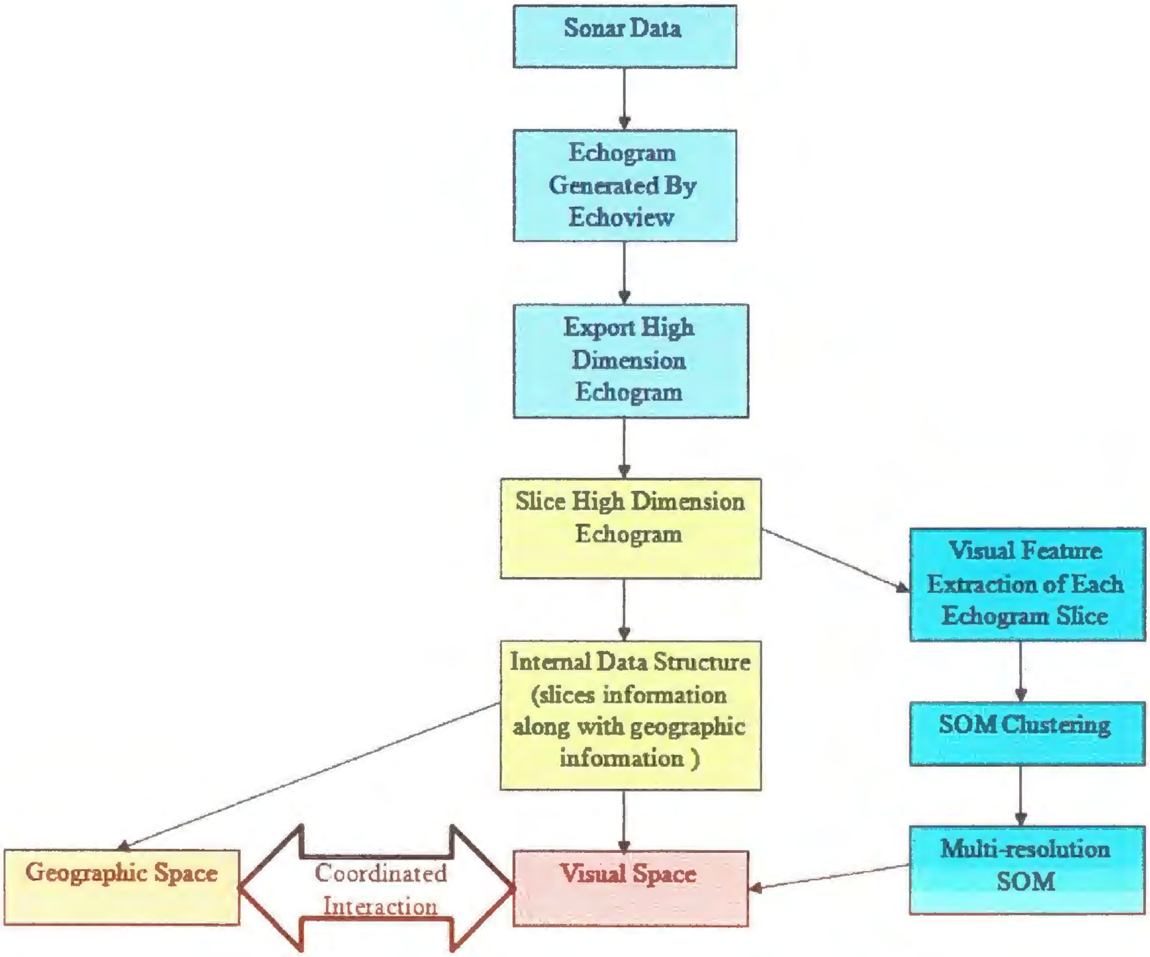


Figure 3.12: Architecture of the GVFO system.

using the Echoview [46] software and then exported as a high dimension echogram. A Java program is used to slice the high dimension echogram width-wise into a large number of smaller echogram slices. After generating the smaller echogram slices, a colour-gradient correlation feature vector is generated to model the visual features of each of the slice. The *visual space* organizes the echogram slices based on their visual similarities. The *geographic space* illustrates the locations of each of the echogram slices. The *visual space* and *geographic space* are linked together using coordinated interaction to support sonar data exploration.

3.4 Discussion

In this chapter, The GVFO system was described in detail. The implementation details of the system were also presented.

The GVFO system consists of pre-processing the data, displaying the data in both a *visual space* and a *geographic space*, and coordinating the interaction between these two views. The visual organization of sonar data (using echogram slices) organizes and clusters echogram slices based on their visual similarities. The key benefit of this approach is that it simultaneously provides an overview of the echogram slices, and a convenient method (zooming) for de-aggregating the implicit clusters as more detail is desired. By making it easy to browse the overall features of the sonar data, the expectation is that such a visual approach will not only give the analysts an ability to readily identify features of interest, but also to find other elements of the sonar data that contain similar data, perhaps at distant locations. This supports analysis activities where the desire is to find relationships among the data.

The geovisual representation shows the locations of the echogram slices. The key benefit of this approach is to support analysis activities to identify the geographic features of interest. By viewing the geographic representation, the analysts are also able to understand in which region the ocean vessel moved to collect the data.

The interactive data analysis in both the *visual space* and *geographic space* follows Shneiderman's [56] popular Visual Information Seeking Mantra: "overview first, zoom and filter, then details-on-demand". The benefit of using this Mantra is that the analysts can be able to see the overview of the echogram slices and their corresponding geographic information simultaneously. Then they can zoom into specific region (visual and geographic) of their interest to filter out uninteresting data. The zooming may take different forms (visual and geographic), and these are done for different purposes. Zooming into *visual space* shows hidden echogram slices and also filter out the uninteresting (visual features) data; zooming into *geographic space* only filter out the uninteresting (geographic features) data. Finally they can see the details of the interesting data (visual features and geographic features).

To support data exploration, both the *visual space* and *geographic space* support coordinated interaction. The key benefit of coordinated interaction such as this is that it provides the analysts with a great degree of freedom with respect to filtering and inspecting the data. In some cases, the analysts may wish to filter the data based on geographic constraints (by zooming into a region of interest in the geographic space). In other cases, an analyst may wish to filter the data based on visual features of interest in the echogram slices (by zooming into a region of interest in the visual space). Or, more likely, the analyst will wish to go back and forth between the two types of filtering as they explore the sonar data. The ability to dynamically focus on a data object in one view and then view its corresponding object in the other supports a disambiguation of the data between the two views.

One potential problem is that slicing the echogram may result in particular features of interest being divided between multiple slices. An echogram slice merging technique is provided within the geographic space to support the analysts in understanding and further analyzing these features. The ability for the analysts to change the width of the echogram slices is also provided within the GVFO system to overcome the slicing problem.

Since geovisual analytics focuses on finding location-related patterns and relationships within a dataset to support exploratory tasks [55], the GVFO system can be considered a geovisual analytics approach for the exploration of sonar data. In this system the patterns of the echogram slices are represented in the *visual space* and the relationships of their corresponding locations are represented in the *geographic space*. This system is designed to enhance the analysts abilities to explore the sonar data based on both the visual features and geographic features simultaneously.

Chapter 4

Evaluation

In the previous chapter, the GVFO system was discussed in detail. Although the examples and analysis provided within that chapter showed the benefits of the approach, further comprehensive evaluations are required to confirm the value of the proposed system for sonar data analysis tasks. The main goal of this evaluation is to address the fundamental research questions that were asked regarding the approach. Due to the specialized nature of sonar data analysis activities, and the small number of knowledgeable participants, a field trial methodology was chosen [57].

4.1 Hypotheses

Based on the observations and knowledge about the GVFO system under investigation, a set of hypotheses were formulated to guide the design of the field trials. These hypotheses are as follows:

H1: *Analysts will find the visual organization of similar echogram slices useful.*

This hypothesis was provided based on the visual organization of the echogram slices. The visual organization of echogram slices form clusters of the slices based on their visual similarity, which helps the analysts to explore interesting patterns within the sonar data. The expectation is that the visual organization of similar echogram slices will be useful for the analysts to explore the data.

H2: *Analysts will find the interaction with the visual organization of the echogram slices easy to use.*

This hypothesis was formulated based on the interaction with the visual organization of the echogram slices. The interaction techniques (panning and zooming) provide an intuitive way to explore the sonar data. The expectation is that interaction with the visual organization of the echogram slices will be easy for the analysts to use.

H3: *Analysts will indicate that they are satisfied with the support the visual organization of the echogram slices provides for their data analysis activities.*

This hypothesis was provided based on the satisfaction of the analysts about the visual organization and interaction techniques of the sonar data exploration. The visual organization groups similar slices near one another and interaction with the visual organization of the slices helps the analysts to explore interesting patterns efficiently. The expectation is that analysts will be satisfied with the support the visual organization of the echogram slices.

H4: *Analysts will find the geovisual organization of the echogram slices useful.*

This hypothesis was provided based on the geovisualization of the echogram slices. The geovisual organization of the echogram slices represents corresponding locations, which helps the analysts to explore interesting geographic patterns within the sonar data. The expectation is that geovisualization matching the echogram features with the locations on the map for the analysts to explore sonar data.

H5: *Analysts will find the interaction with the geovisual organization of the echogram slices easy to use.*

This hypothesis was also formulated based on the interaction with the geovisualization of the locations of the echogram slices. The interaction techniques (panning and zooming) provide an intuitive way to explore the sonar data. The expectation is that interaction with the geovisualization of the locations of the echogram slices will be easy for the analysts to use to explore sonar data.

H6: *Analysts will indicate that they are satisfied with the support the geovisual organization of the echogram slices provides for their data analysis activities.*

This hypothesis was provided based on the satisfaction of the analysts about the geovisual organization and interaction techniques of the sonar data exploration. The geovisualization represents corresponding locations of echogram slices and interaction with the geovisual organization of the slices helps the analysts to explore interesting geographic patterns efficiently. The expectation is that analysts are satisfied with the support the geovisualization of the locations of the echogram slices provides for their data analysis activities.

H7: *Analysts will indicate that their understanding of the relationships between the echogram slices is enhanced due to the coordinated interaction because it is useful and easy to use.*

This hypothesis was formulated based on coordinated interaction between the visual organization of the echogram slices and the geovisualization of the locations of the echogram slices. The coordinated interaction allows the analysts to explore sonar data simultaneously based on visual organization and geovisual organization. The expectation is that the coordinated interaction allows the analysts to understand the relationships between the echogram slices and geovisualization of the echogram slices.

H8: *Analysts will indicate that they find the ability to highlight echogram slices to show their corresponding locations useful and easy to operate.*

This hypothesis was formulated based on coordinated interaction between the visual organization of the echogram slices and the geovisualization of the echogram slices. Selecting the echogram slices highlights the locations that allows the analysts to examine the echogram slices in details along with their locations. The expectation is that highlighting of echogram slices locations allows the analysts to understand the relationships between the echogram slices and their geographic locations.

H9: *Analysts will indicate that they find the ability to highlight echogram slice locations to show the corresponding echogram slice useful and easy to use.*

This hypothesis was formulated based on coordinated interaction between geovisualization and visual organization of the echogram slices. Selecting the locations allows the analysts to inspect the details of the echogram slices. The expectation is that the coordinated interaction allows the analysts to understand the relationships between the geographic locations of the echogram slices.

H10: *Analysts will indicate that they find the ability to merge the echogram slices useful and easy to use.*

This hypothesis was provided based on how useful the ability to merge the echogram slices is. Merging of echogram slices mitigates the risk of dividing interesting features of the sonar data. The expectation is that the ability to merge the echogram slices provide a larger echogram slice that can then be examined in detail, as required by the analysts.

4.2 Methodology

The field trial methodology used in this thesis provides a realistic test of the GVFO system by allowing expert participants to use real data to perform their usual tasks [57]. This enables the participants to provide informed opinions about the ability of the system to support their real-world work activities, leading to a more reliable assessment. While field trials do not provide comparable quantitative data due to the open-ended nature of the tasks and the small number of participants, they do provide insightful qualitative feedback from actual data analysts, which is much more valuable than the statistical analysis of quantitative data measured over contrived tasks [11].

4.2.1 Experimental Setup

A multi-display computer environment consisting of a 46" LCD TV screen (1920 $\times$ 1080 pixels) and a 27" iMac computer (2560 $\times$ 1440 pixels) system was used in this study for simultaneous exploration of visual features and geographic features of the sonar data (see Figure 4.1). The TV screen shows the visual space and the computer screen shows the geographic space. The key benefits of this setup are that the large screen TV can display a large number of echogram slices with sufficient detail, along with the geographic information of the corresponding echogram slices displayed in iMac computer system allowing analysts to seek interesting features within the data simultaneously. Although not studied in these field trials, another benefit of this setup is that it allows for multiple data analysts to work together in the exploration of the echogram slices as a result of displaying these on the large screen TV.

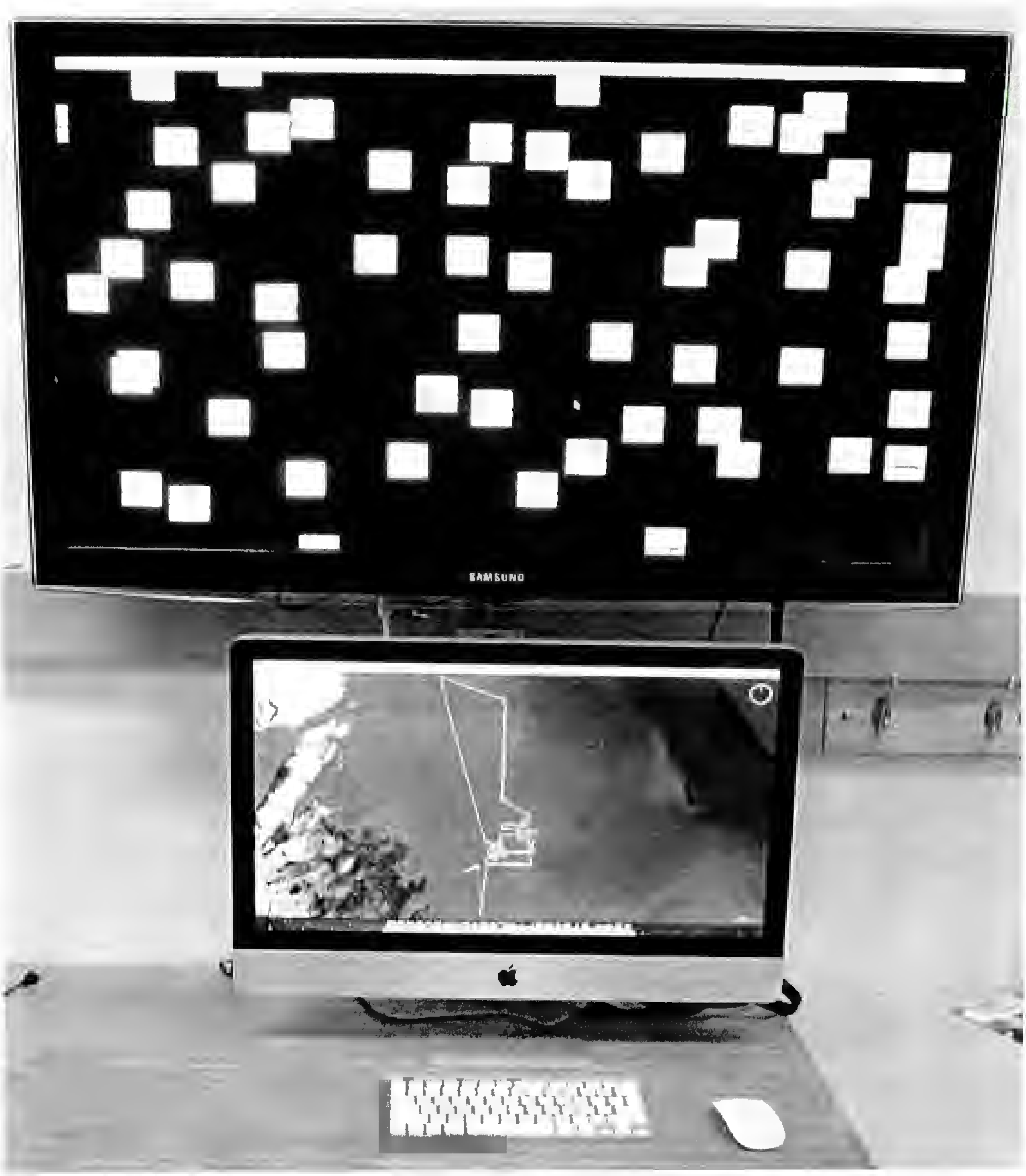


Figure 4.1: The lab setup running the GVFO system consisted of a 46" LCD TV screen (visual space) and a 27" iMac (geographic space).

A sonar dataset collected by a 38-kHz split-beam SIMRAD EK500 echosounder device was used in the experiments (note that this is the same data set described in Section 3.2.5). This data was measured in the Bonavista Corridor in the North Atlantic Ocean, with the path of the sonar data covering 1040 km and the data consisting of 151,836 sonar pings. This data was used to generate a high-dimensional echogram using the Echoview software, at a resolution of $151,836 \times 1000$ pixels. This echogram was extracted from Echoview and sliced into 152 individual 1000×1000 pixel echogram slices. The geographic locations of the mid-points of each echogram slice were extracted from the raw sonar data, and matched with the corresponding echogram slice.

4.2.2 Study Procedures

In the field trials, at the very first the consent forms were presented to the participants and obtained consent to participate in this study. Then each participant was asked to complete a pre-study questionnaire. Different types of questions were asked in the questionnaire about the demographics of the participants.

After completing the pre-study questionnaire, all the participants were instructed by the investigator about how to use the GVFO system. This was done as part of the training phase. The investigator assisted the participant in performing the tranning task, showing them features of the software that can be of assistance, and explaining to them how the GVFO system works.

After training the participants, they were asked to explore the sonar data based on both the visual features and geographic features. The participants simultaneously sought interesting features and patterns within the data by using multiple coordinated views (*visual space* and *geographic space*). In the field trials each participant used the same sonar data set, and they performed open-ended data analysis tasks based on their own interests and experience.

After using the system in an open and undirected exploration of the data, each participant was asked to complete a questionnaire. Different types of questions were asked in the post-study questionnaire to measure the usefulness, ease-of-use, satisfaction, and understanding of different features of the GVFO system. For the usefulness and ease-of-use measure, a set of six questions were asked of each participant, drawn from the Technology Acceptance Model [14]. For the satisfaction measure, a set of three questions were asked of each participant, focusing on their ability to explore visual features within *visual space* and geographic features within *geographic space*. For the understanding measure, a set of three questions were asked of each participant, focusing on their ability to make connections between the echogram slices represented in the two views.

The data was measured on 5-point Likert scales, with the range of responses: strongly agree, agree, neutrality, disagree, and strongly disagree. The questions focused on measuring the participants' perceptions related to five key features of the system (see Appendix B).

A set of semi-structured interviews were also conducted to examine the participants' opinions and experiences after using the GVFO system. Since the post-study questionnaire only covers a few specific questions regarding the participants' perceptions, interviews allow them to provide a broader range of responses on issues and topics that were not asked in the post-study questionnaire.

During the participants' data analysis tasks, the investigator also observed the way in which they used the GVFO system. These observations were expected to be helpful to analyze the results based on the participants' data analysis activities.

In this thesis, quantitative data on the participants' performance was not collected and the participants did not perform prescribed tasks; instead they were permitted to explore the data in any manner they chose. The reason for this is that the GVFO system was not directly compared with any other baseline system that supports visual organization and geographic organization of the data simultaneously. Since no such baseline system exists, it is not useful to measure the quantitative data for different data analysis tasks of the participants to evaluate the GVFO system.

4.2.3 Data Analysis

Different types of data collection methods are used in this study such as post-study questionaire, interview responses, and investigator observations. To analyze these data different types of data analysis methods are used.

The sets of questions (post-study questionaire) each addressed the participants' perceptions from multiple perspectives on a common underlying feature (e.g., the usefulness of the visual space). For data analysis purposes the data are aggregated based on each key feature of the system listed above. However, since each participant had the opportunity to analyze the data differently, aggregating the data over the participants is not useful. This data is visually depicted using histograms, and discussed in Section 4.3.1 - 4.3.5. In this study no statistical analyses were performed. Since no quantitative data was collected in this study, as such it is meaningless to perform statistical analysis.

Interviewing of the participants allows them to express their opinions broadly about different features of the GVFO system. Each of the comments made in the interviews were coded according to the three classes (positive responses, negative responses, and improvements and new feature of the system), and then these statements were grouped to observe common themes. The responses to the interviews are discussed in Section 4.3.6.

Investigator observations provide a way to assess participants live activities with the system. How the participants used the different features (visual organization, geographic organization, coordinated interaction, echogram slice merging, and adjusting echogram slice size) of the system for their data exploration tasks were grouped to identify common themes. The investigator's observations are discussed in Section 4.3.7.

4.2.4 Participants

Five participants were purposefully recruited from among the employees and senior graduate students within a marine research laboratory. Here, the participants are denoted as P1. P2. P3. P4. and P5. The participants were selected based on their experience and regular analysis of sonar data. All of the participants reported having a high degree of understanding of sonar data visualization, were experienced users of Echoview, and had a moderate to high degree of familiarity using virtual globes like Google Earth. There was some difference in how long they have been performing sonar data analysis, their experience with visually organized images, and their fa-

Table 4.1: Participant demographics of the field trials evaluation

	P1	P2	P3	P4	P5
Sonar data analysis experience	3 years	10 years	8 years	1.5 years	2 years
Sonar data analysis software system	Echoview	Echoview, EP500, FASIT	Echoview, Simrad, FASIT	Echoview, Visual Acquisition, QTC	Echoview
Sonar data visualization experience	very high	very high	very high	high	very high
Familiarity with virtual globes	very familiar	very familiar	medium	medium	familiar
Experience with image organization	moderate	moderate	moderate	no	no
Familiarity with MCVs	familiar	not familiar	moderate	moderate	moderate

miliarity with multiple coordinated views (MCVs). Based on these prior experiences and familiarity with sonar data analysis software, it can be concluded that the five participants in this study represent a somewhat broad spectrum of expert sonar data analysts. The participants demographics were collected in a pre-study questionnaire and are listed in Table 4.1.

4.3 Results

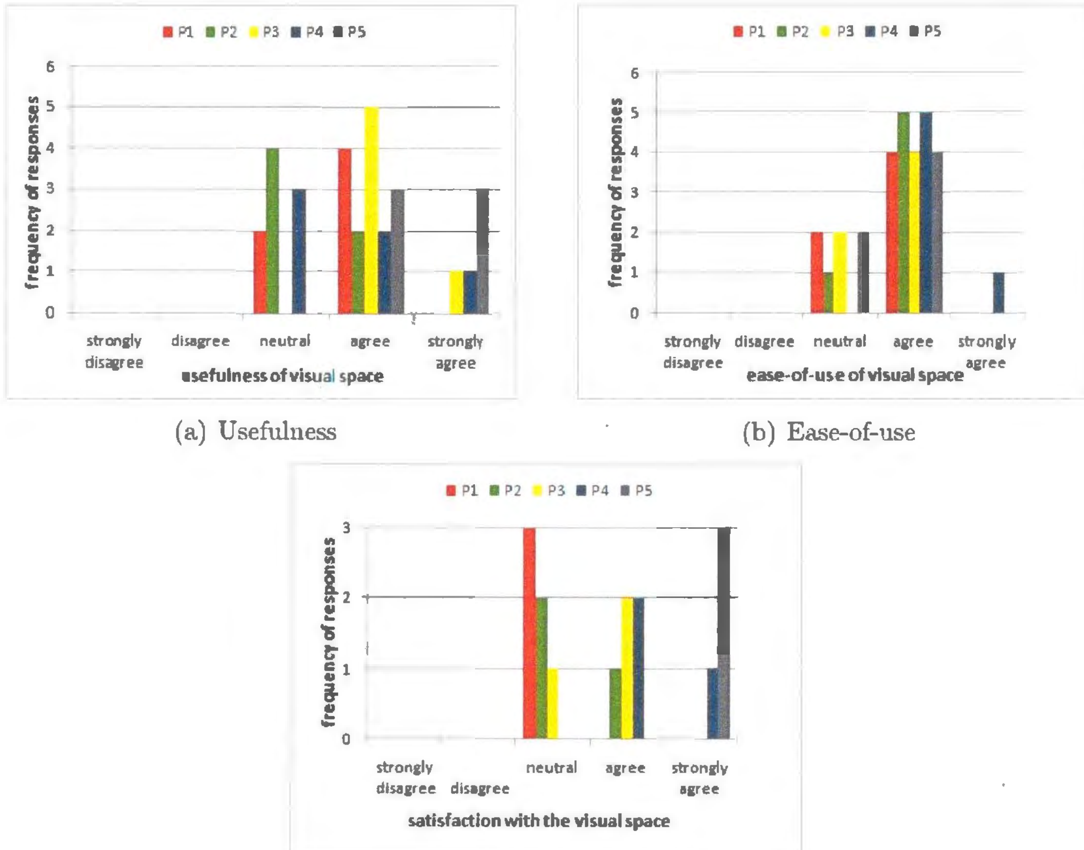
In the course of these field trials, a number of specific measurements were taken in order to observe participants' subjective reactions and opinions of the GVFO system. In this section, the results from each of these measures are discussed in detail and linked back to the previously stated hypotheses to assess the GVFO system.

4.3.1 Visual Organization of the Echogram Slices

One of the core features within the GVFO system is the visual organization of the echogram slices. This feature organizes echogram slices based on their visual similarities forming a hierarchical clustering of the slices. This clustering groups similar echogram slices near one another and dissimilar echogram slices are placed far away.

The perceived usefulness, ease-of-use, and satisfaction reported by the participants for the visual organization of the echogram slices are represented in Figure 4.2. For the perceived usefulness. the responses ranged from neutral to strongly agree; some participants (P1, P2, and P4) provided more neutral responses whereas others leaned towards agreeing (P3) or strongly agreeing (P5) with the statements regarding the usefulness of the visual representations of the system. Some participants were able to see the value of the approach for analyzing sonar data, whereas others were more pessimistic or reserved in their opinions. However, none of the participants indicated that the features were not useful. which can be considered a positive finding. Hypothesis H1 predicted that the participants would find the visual organization of the echogram slices useful. These findings support this hypothesis.

The participants responses regarding the perceived ease-of-use of the visual organization of the echogram slices are represented in Figure 4.2(b). Although some participants (P1, P2, P3, and P5) reported some neutral responses, most of the participants agreed with the statements regarding the ease-of-use of the visual organization of the echogram slices. Hypothesis H2 anticipated that the participants would find the interaction with the visual organization of echogram slices easy to use. The findings also support this hypothesis.



(a) Usefulness

(b) Ease-of-use

(c) Satisfaction

Figure 4.2: Frequency of responses to six questions each regarding the usefulness (a) and ease-of-use (b) of the visual space. Frequency of responses to three questions regarding the satisfaction (c) with the visual space.

The perceived satisfaction indicates whether participants were satisfied with the support the visual organization of the echogram slices provided for their data analysis activities. The participants' perceived satisfaction of the visual organization of the echogram slices is represented in Figure 4.2(c). Some participants (P1, P2, and P3) reported some neutral responses, whereas others leaned towards agreeing (P4) or strongly agreeing (P5) with the statements regarding the satisfaction with the visual organization of the echogram slices. Hypothesis H3 indicated that the participants would be satisfied with the visual organization of the echogram slices for their data analysis activities; the results support this hypothesis.

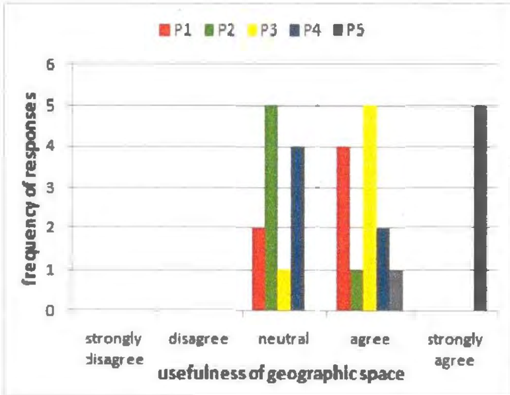
4.3.2 Geovisual Organization of the Echogram Slices

Another core feature within the GVFO system is the geovisual organization of the echogram slices. This feature of the system shows the corresponding geographic location of each echogram slice on a virtual globe, with the goal of enhancing the ability of the analysts for exploring the geographic features of the data. The value of this feature is addressed by particular classes of questions in the post-study questionnaire.

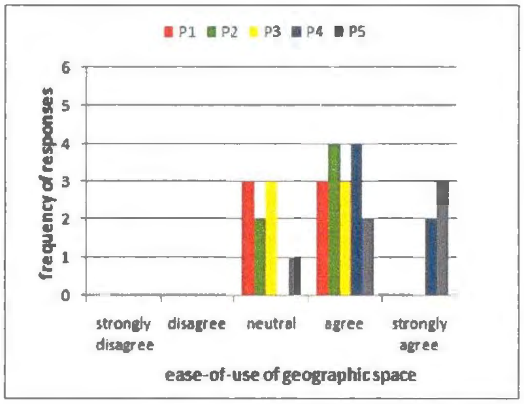
The perceived usefulness, ease-of-use, and satisfaction reported by the participants for the geovisual organization of the echogram slices are represented in Figure 4.3. In all cases, the responses ranged from neutral to strongly agree.

The participants' perceived usefulness of the geovisual organization of the echogram slices is represented in Figure 4.3(a). Some participants (P2 and P4) provided more neutral responses whereas others agreed (P1 and P3) or strongly agreed (P5) with the statements regarding the usefulness of the geovisual representations of the system. Hypothesis H4 predicted that the participants would find the geovisual organization of the echogram slices useful; the results support the hypothesis.

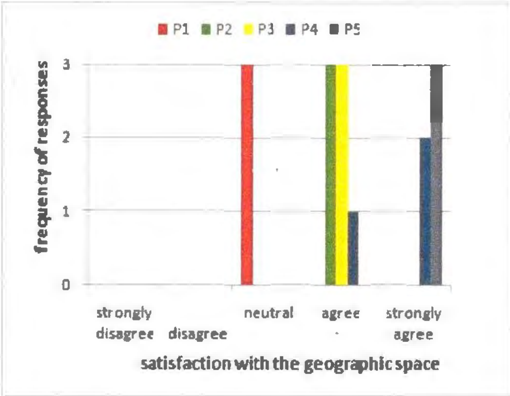
The participants' perceived ease-of-use of the geovisual organization of the echogram slices is represented in Figure 4.3(b). The responses were almost evenly distributed from neutral to strongly agreeing range. Although all the participants agreed with the statements regarding the ease-of-use of the geovisual organization of the echogram slices, some participants (P1, P2, P3, and P5) reported some neutral responses. None of the participants indicated that the features were not easy to use, which can be con-



(a) Usefulness



(b) Ease-of-use



(c) Satisfaction

Figure 4.3: Frequency of responses to six questions regarding the usefulness (a) and ease-of-use (b) of the geographic space. Frequency of responses to three questions regarding the satisfaction (c) with the geographic space.

sidered a positive outcome. Hypothesis H5 anticipated that the participants would find the interaction easy to use with the geovisual organization of echogram slices. The findings support this hypothesis.

The participants' perceived satisfaction of the geovisual organization of the echogram slices is represented in Figure 4.3(c). P1 had a strong neutral perception of this feature, whereas others provided agreeing (P2 and P3) or strongly agreeing (P4 and P5) responses with the statements regarding the satisfaction of the geovisual representations of the system. Since all of the participants except P1 indicated that they were satisfied with the geovisual representation of the system for their data analysis activities it shows promise of the satisfaction. Hypothesis H6 indicated that the participants would be satisfied with the geovisual organization of the echogram slices for their data analysis activities. The analysis of results also support this hypothesis.

4.3.3 Understanding of the Relationship Between the Visual and Geographic Spaces

An important feature within the GVFO system is the coordinated interaction between the visual and geographic spaces. Each echogram slice was included in both spaces, although in the visual space a particular echogram slice could have been hidden depending on the level of zoom. The value of coordinated interaction was measured in such a way where the participants were able to understand the relationships between the data shown in the visual and geographic views.

The participants' perceived understanding of the relationships between the visual and geographic spaces is represented in Figure 4.4. Although one participant reported some neutral responses, the others agreed or strongly agreed with the statements regarding the understanding of the relationships between the data shown. These results indicate that most participants were able to readily understand the connections between the two visual representations of the data, supporting the value of providing multiple linked representations. Hypothesis H7 indicated that coordinated interaction would enhance participants' understanding about the relationships between the echogram slices; the results support this hypothesis.

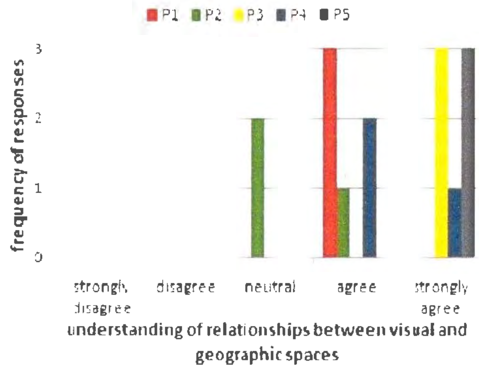
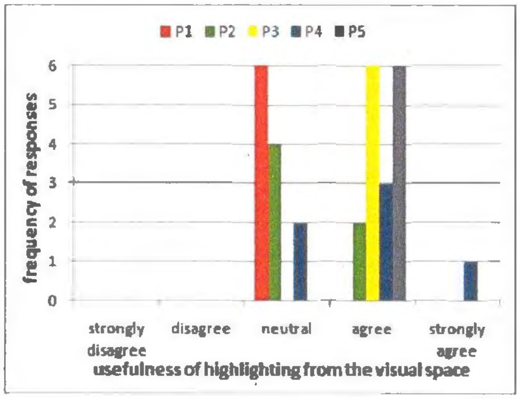


Figure 4.4: Frequency of responses to three questions regarding the understanding of the relationships between the echogram slices shown in the visual and geographic spaces.

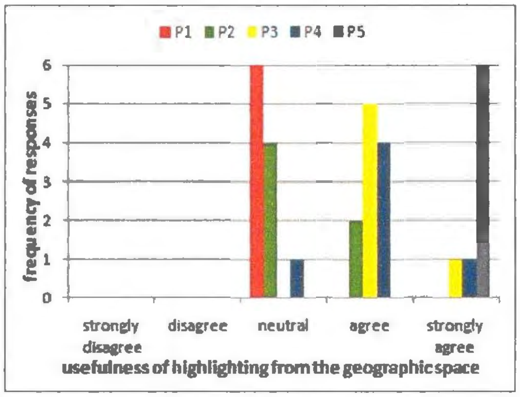
4.3.4 Echogram Slice Highlighting

The perceived usefulness of the highlighting of echogram slices was measured from two perspectives: selecting an echogram slice to highlight a glyph in the geographic space: or selecting a glyph to highlight an echogram slice in the visual space. The participants responses to the usefulness questions from these two perspectives are represented in Figure 1.5.

The responses ranged from neutral to strongly agree. P1 had a strong neutral perception of these features, based on a negative perception of the multi-display setup on which the study was conducted, which came up during the interviews. Not considering this participants' responses, the results illustrate the benefit of allowing the data shown in one space to be highlighted in the other. Hypothesis H8 and H9 predicted that participants would find the ability to highlight echogram slices or to highlight echogram slice locations useful. These findings support both hypotheses.



(a) Usefulness of highlighting from the visual space



(b) Usefulness of highlighting from the geographic space

Figure 4.5: Frequency of responses to six questions regarding the usefulness of the highlighting when selecting an object in the visual space to highlight it in the geographic space (a), and selecting an object in the geographic space to highlight it in the visual space (b).

4.3.5 Usefulness of Echogram Slice Merging

One of the potential problems with turning a large echogram into many smaller echogram slices is the potential for slicing the echogram over a feature of interest. As such, an echogram slice merging feature was included in the GVFO system. The perceived usefulness of merging multiple echogram slices into a larger echogram slice are represented in Figure 4.6. In almost all cases, participants indicated agreement or strong agreement with the statements related to this feature. This finding, while strongly positive, is not surprising. All of the participants were experienced users of Echoview, where the default representation of echograms is in short but wide views. The merging of echogram slices in the GVFO system produced echogram slices that are in a format that was very familiar to all of the participants. As a result, their positive responses are likely due to their familiarity with this format of the data. Hypothesis H10 indicated that participants would find the ability to merge

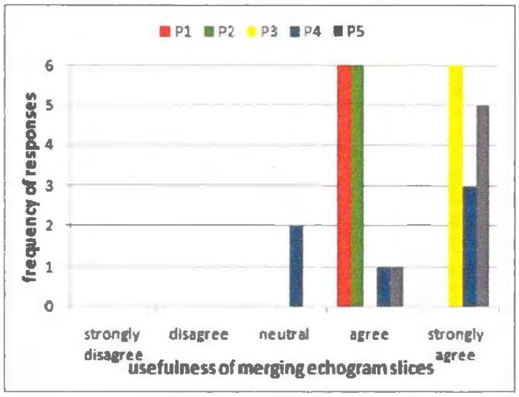


Figure 4.6: Frequency of responses to six questions regarding the usefulness of merging a subset of the echogram slices into one larger echogram slice.

the echogram slices useful, and the results support the hypothesis.

4.3.6 Interview Responses

At the end of the study, a semi-structured interview was conducted (see Appendix B) with a list of questions that focused on specific aspects of using the GVFO system. While most participants provided positive feedback in favour of the GVFO system, some commented on their difficulties to use the system, and also on how to improve the system. The key elements are discussed and outlined below.

4.3.6.1 Positive Responses

All five participants stated that they liked the idea of the visual organization of the echogram slices. For example, P3 noted that, "This system has the ability to see the whole picture that groups together the echogram slices based on similar characteristics". P1 commented, "I like the possibility of being able to look at species distributions quickly".

All of the five participants also liked the idea of the geospatial organization of the echogram slices. P4 stated, "This is really a good feature of the system. I can choose echogram slices and it shows me on the map where I can find similar signals". P3 noted, "It is helpful to see the exact locations of different echogram slices". P5 also stated, "It is really nice to have the feature of looking at the echogram slices with their locations".

All five participants stated that they liked the coordinated interaction between visual space and geographic space. They found the ability to merge the echogram slices helpful. P5 stated, "I can look at the whole area by using the merge feature and see if anything is there in terms of fish or others based on my choice of interest". P1 noted, "I don't know any other software that analyzes sonar data and looks for patterns across distant geographic ranges. So this is the first one that I have seen, which provides merging feature".

In general, all the participants liked different features of the GVFO system. A few of general comments of the different participants included "It could be a useful learning tool for training new people about sonar data", and "It is an interesting system that shows promise in fisheries survey".

4.3.6.2 Negative Responses

Some participants commented on their difficulties in using the different features of the system. P3 noted, "It will be more easier to interact with the geographic position if the size of each glyph is a bit larger". P2 said, "Learning the system requires some effort at the initial stage. Sometimes I forget about how to close the merged echogram slices window". P1 did not like the use of two screens for coordinated interaction and said, "If you have all the information in one panel, so that I can see both of the information at the same time without looking at two different screens, then it will be much easier".

One hour (including training session) is allocated for each participant to use the system in this field trials. Since all of the participants were not familiar with GVFO system before, it took some time to get adjusted with the system. Further training and experience may alleviate these concerns.

4.3.6.3 Improvements and New Features

Some participants also gave some suggestions regarding the way in which the system can be improved. P1 said, "You can use different kinds of data that contain different kinds of signals for different species and then see in which way your system forms the cluster of the echogram slices". P5 stated, "It could also be useful if I could select multiple echogram slices from the visual space and merge these slices together along with their corresponding positions within the geographic space. Because, then I could say whether these slices represent fish signals or noisy signals and highlight their positions at distant geographic ranges". This input is valuable for further refinements.

4.3.7 Investigator Observations

The investigator observed the way in which participants used the system for their data analysis tasks. In most cases, the participants started the analysis and exploration of the data within the visual space. Since the visual space clusters the echogram slices based on their visual similarities, doing so could allow the analysts to identify a feature of interest among the collection of echogram slices. Four (P1, P3, P4, and P5) out of five participants focused on an area within visual space in which the echogram slices contained data associated with fish schools (see Figure 4.7), whereas the other participant (P2) was interested in echogram slices that contained noisy signals (see Figure 4.8). These differences may have been due to the different types of data analysis that the participants normally perform with such data.

All the participants zoomed into the visual space and highlighted individual echogram slices and their corresponding geographic positions. They also zoomed into the geographic space, highlighted individual geographic positions and their corresponding echogram slices. This zoom operation allowed participants to perform further fine-tuning within either the visual space or the geographic space.

During the data analysis tasks, all the participants showed an interest in seeing contextual information around a particular group of echogram slices. Initially they started by highlighting specific geographic positions of the feature of interest. Then they merged these back together to form a larger echogram slice in order to find interesting features for the ordered geographic positions. Doing of this task indicates that they may have preferred the slices to be wider. The possible reason of preferring wider echogram slices might be that Echoview always produces wider echograms and they are familiar with analyzing wider echograms in existing practice. All the participants did this frequently during their data analysis tasks.

P3 tried to select multiple echogram slices from the visual space and marge these back together to show a larger echogram slice. GVFO system does not support this feature because the selected slices may not be from the same geographic region. The merging only makes sense for ordered echogram slices, which can be selected from the geographic space but not from the visual space.

Three participants (P2, P3, and P5) adjusted the sizes of the echogram slices

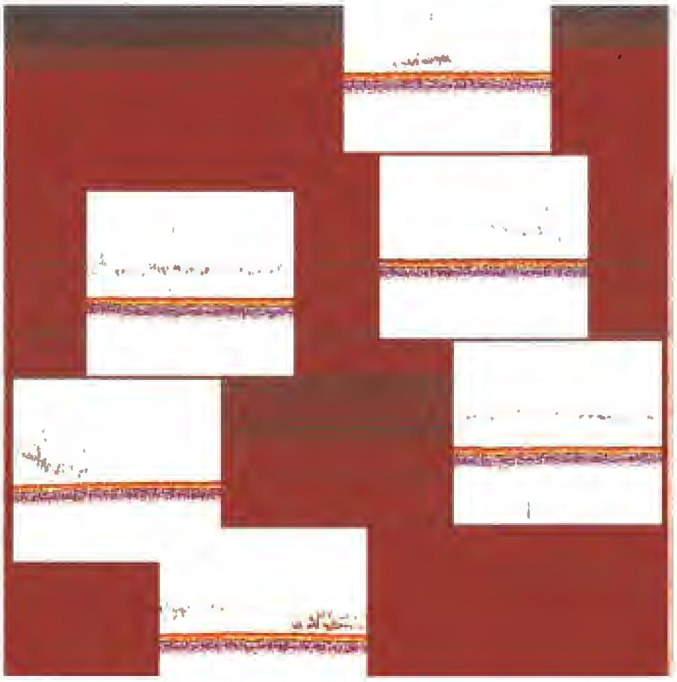


Figure 4.7: Echogram slices contained data associated with fish schools.

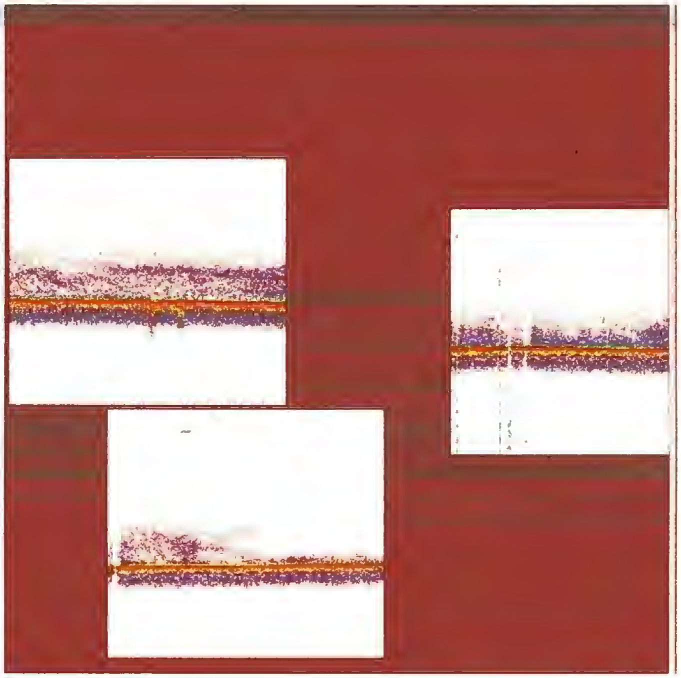


Figure 4.8: Echogram slices contained data associated with noisy signals.

during their analysis activities. When they made the echogram slices wider, they were able to see larger features within the data, and reduced the chance of dividing an interesting feature between two or more echogram slices. However, with this smaller number of larger echogram slices, the ability for the system to effectively cluster the echogram slices based on the visual features was affected. Conversely, when these participants made the echogram slices smaller, small features were effectively captured within the echogram slices, and the quality of the visual clustering improved. However, this was done at the expense of potentially dividing an interesting feature among multiple echogram slices. The participants appeared to appreciated the value of interactively manipulate the echogram slice sizes as they explored the data.

4.4 Discussion

In this evaluation, field trials using expert participants were conducted in a real-world data analysis environment to validate the potential value of the proposed GVFO system. The multi-display setup allowed the analysts to explore the sonar data simultaneously based on both visual features and geographic features. The multi-display setup that has been used in these field trials consist of two screens arranged vertically.

In these field trials, some participants were quite neutral about some features, although none disliked anything. Others were quite positive. It can be concluded that the findings are supportive of the hypotheses, although there was some element of neutrality. Although the participants' perceptions of the usefulness and ease-of-use of the visual organization and geovisual organization of the echogram slices were matched closely, the participants' perceptions of satisfaction of the geovisual organization was better than for the visual organization of the echogram slices. The participants did not have any facilities in their current data analysis tools to simultaneously explore the geographic features with the visual features of the echogram in their existing practice of sonar data analysis. Since the GVFO system provides this facility, they proved to be more satisfied with the geovisual organization of the data.

Considering only P2-P5, there is an interesting pattern that emerged when comparing the data regarding the usefulness of the visual space and the geographic space. In particular, the participants' perceptions of the usefulness of the visual space matched closely with their perceptions of the usefulness of highlighting an echogram slice starting from the visual space. A similar pattern is present when comparing the perceptions of usefulness for the geographic space and the usefulness of highlighting an echogram slice starting from the geographic space. These patterns indicate a preference of some participants for analyzing the data focusing on the visual features of the echogram slices, whereas others preferred to start form the geographic features.

Another interesting finding was that the usefulness of the echogram slice merging feature is strongly positive. A possible reason for this is that all the participants were experienced users of Echoview. The echogram slice merging feature of the GVFO system produced echogram slices that are in a format that was very familiar to all the participants. Moreover, this feature allowed the participants to analyze larger portion of echogram slices (multiple echogram slices) at a time.

Participants easily expressed their opinions and experiences after interviewing them. Although most of the participants liked different features of the system, some participants' also commented on their difficulties to use the some features. Some participants also provided suggestions to improve the system. One interesting finding was that P1 did not like the using of the two screens for the coordinated interaction. Another interesting finding was that the participants were all interested in using the sonar data for fish stock assessment. Since the sea floor has a strong visual presence in the echogram slices, it was sometimes a prominent factor in the visual similarity calculations. In some cases, for fish stock analysis, it would be beneficial to remove the sea floor in order to focus on the fish. However, in other cases, the sea floor is the important element.

Observation of participants activities with the system allowing the investigator to analyze these in depth. The interesting observation was that most of the time most of the participants were interested in those echogram slices that hold fishing school signals in their visual similarities or they were interested in those geographic locations where the ocean vessels moved frequently to collect the data. A possible reason of this is that most of the time they analyze sonar data to find fish schools.

The analysis of the results of the field trials showing that the GVFO system enhances the existing practice of the sonar data exploration tasks. The real-world environment allowed the participants to perform the data analysis tasks according to their own needs, resulting in valuable insights into the usability and utility of the GVFO system.

Chapter 5

Conclusions and Future Work

The goal of this thesis has been to address fundamental issues related to the shortcomings of the existing practice of analyzing marine sonar data. To fulfill this goal, an approach that takes advantage of geovisual analytics to support the data analysis tasks was introduced. This approach couples a technique for visually clustering slices of the echogram based on visual similarity (*visual space*), with a geovisualization method that shows the spatial location of the echogram slices on a virtual globe (*geographic space*). Both of these spaces support pan and zoom operations, which can be used to focus on the area of interest or to change the region of focus as necessary.

These two spaces are also operated as multiple coordinated views. Panning and zooming within each of these views of the data results in coordinated filtering, such that data outside of the viewport in one view is dimmed and de-emphasized in the other view. In particular, analysts may filter the data based on spatial regions of interest, visually identify important features within the data, and observe the spatial relationships among the locations of the echogram slices (as described in Chapter 3).

Field trials were conducted with real-world data analysts to illustrate the benefits of the spatial and visual feature organization approach (as described in Chapter 4). By using this approach, participants in this study analyzed sonar data, seeking interesting patterns within the data. The remainder of this chapter summarizes the contributions of the research work presented in this thesis, and potential future research directions.

5.1 Research Contributions

Although analyzing marine sonar data using echograms is a common approach, it suffers from the problems of requiring analysts to scroll back and forth during the data analysis process, and from the lack of representation of the geospatial features of the data. As such, exploring the data requires additional cognitive load as the analysts attempt to keep track of the geospatial locations of the features while they analyze the echogram.

The GVFO system has been developed with the purpose of allowing analysts to more readily identify similar patterns and features within an echogram (even if these are geographically distant), and to provide flexible methods for filtering the data. The system provides two views of the data: a visual space that provides a visual organization of the echogram slices, and a geographic space that illustrates the locations of the echogram slices on a virtual globe.

Field trials were conducted to measure the perceived usefulness, ease-of-use, and satisfaction of the main features of the system, along with the perceived understanding of the relationships between the two views of the data. In general, the responses of the participants were collected via questionnaires after the field trials. The responses ranged from neutral opinions to strongly positive opinions for different features of the GVFO system.

An interview was conducted after running the GVFO system to get a boarder range of feedback regarding the system. Although most of the participants provided positive feedback about the GVFO system, some participants commented on their difficulties to use the system, and also commented to add new features to improve the system.

A fundamental research question raised about the visual organization and geovisualization of the locations of the echogram slices was, *does the visual organization of the echogram slices along with the geovisualization of the locations enhance the ability of analysts to explore echograms?* The expectation was that both the visual organization and geovisualization of the locations of the echogram slices would be useful, easy to use, and also enhance the satisfaction of the analysts for their data analysis activities. From the results of the field trials, it was found that all the hypotheses (H1, H2, H3, H4, H5, and H6) related with aforementioned research questions were supported (see Section 4.3.1 - 4.3.5).

The visual space and geographic space are linked together to support coordinated interaction. Analysts can pan and zoom within both spaces, such that data filtered out in one view are automatically dimmed in the other. The research questions emerging for this feature was *does the coordinated interaction between the visual space and the geographic space enhances the ability of analysts to understand the relationships between the echogram slices?* The expectation was that coordinated interaction enhances analysts' understanding of the relationships between the echogram slices. It was found that the hypothesis (H7) related with aforementioned research question is supported (see Section 4.3.3).

An Echogram slice highlighting feature was provided to further enhance the support provided for exploring the data, comparing echogram slices, and for understanding the relationships among the data. A fundamental research question raised about this feature was *does the ability to highlight an individual echogram slice and its corresponding geographic location enhances the ability of analysts to explore echograms?* The expectation was that highlighting echogram slices is useful for analysts' data analysis activities. From the results of the field trials, it was found that hypotheses H8 and H9 are supported illustrating the benefit of highlighting echogram slices and their locations (see Section 4.3.4).

A feature for merging echogram slices was also provided to further enhance the support for exploring the data, comparing echogram slices, and for understanding the relationships among the data. A fundamental research question raised about this feature was *does the ability to merge echogram slices mitigate the risks associated with slicing the echogram over features that might be important?* The expectation was that merging echogram slices is a useful feature that mitigates the risk of slicing an echogram through specific features of interesting data. From the results of the field trials, it was found that hypothesis H10 is also supported, addressing the corresponding research question (see Section 4.3.4).

Participants' opinions and experiences of using the GVFO system were collected via the responses to the interviews. Responses to the interviews were categorized based on three themes positive responses, negative responses, and improvement and new features of the system. Positive responses further supported the answers to the research questions. Negative responses can be used as a motivation along with the suggestions (improvements and new features) regarding the ways in which the system can be improved in future.

5.2 Future Directions

Since the GVFO system was developed as a prototype system that acted as a proof-of-concept for visually organizing echogram slices and providing a coordinated geospatial representation of the data. there is much work that can be done to refine the approach. There are some important new features that could enhance the analysis activities of the users. Instead of using the raw echogram data within the system, it would be useful to allow analysts to first pre-process the data to remove uninteresting features such as the ocean floor (e.g., when performing fisheries analysis). Doing so will allow the visual organization of the echograms to occur based on the interesting features of the data in which the analysts are interested.

Another avenue for further research is to use computer vision techniques [20] to determine the locations of potentially interesting features in the echogram, using this information to avoid slicing such features when generating the echogram slices. Allowing the analysts to add additional information to individual echogram slices, and visually representing this information within the geographic space, would further enhance their ability to analyze the data and understand the relationships between the sub-sea phenomena being explored and the geographic relationships of these phenomena.

In this thesis the colour-gradient correlation feature vector has been used to extract the visual feature of the echogram slices. The reason for using this feature vector is that it is efficient to calculate and provides good organizational performance for images. Other future work could include analyzing the differences between different feature vector methods within the context of visually clustering echogram slices.

To visualize the clusters of the echogram slices based on their visual similarity, a SOM technique has been used in this thesis. Although SOM offers many advantages to cluster and visualize high-dimensional data, it also suffers from a number of disadvantages such as requiring necessary and sufficient data in order to develop meaningful clusters, and being computationally expensive. Another direction for future work includes studying the benefits and drawbacks of different alternatives for visually organizing the echogram slices, such as multidimensional scaling [13].

Although the features of the GVFO system were designed to support knowledge discovery within marine sonar data, the type of analysis it supports may also be beneficial in other domains where there are a large number of images that contain corresponding spatial data, such as sub-sea images, satellite imagery, and traffic analysis. Further evaluation of the approach in these settings is warranted.

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Appendix A

Approval of the User Study

This appendix includes the formal approval received from the Interdisciplinary Committee on Ethics in Human Research (ICEHR) for the study.

MEMORIAL UNIVERSITY

Interdisciplinary Committee on Ethics in Human Research (ICEHR)

ICEHR Number:	20121609-SC
Approval Period:	June 8, 2012 – June 30, 2013
Funding Source	Supervisor's NSERC grant
Responsible Faculty	Dr. Orland Hoeber Department of Computer Science
Title of Project	*Field Trials with Geovisual Analytics Software for Exploring Sonar Data*

June 8, 2012

Mr. Asikur Rahman
Department of Computer Science
Memorial University of Newfoundland

Dear Mr. Rahman:

Thank you for your email correspondence of May 31 and June 5, 2012 addressing the issues raised by the Interdisciplinary Committee on Ethics in Human Research (ICEHR) concerning the above-named research project.

The ICEHR has re-examined the proposal with the clarification and revisions submitted and is satisfied that concerns raised by the Committee have been adequately addressed. In accordance with the *Tri-Council Policy Statement on Ethical Conduct for Research Involving Humans (TCPS2)*, the project has been granted *full ethics clearance* to June 30, 2013.

If you intend to make changes during the course of the project which may give rise to ethical concerns, please forward a description of these changes to Theresa Heath at icehr@mun.ca for the Committee's consideration.

The TCPS2 requires that you submit an annual status report on your project to the ICEHR, should the research carry on beyond June 30, 2013. Also to comply with the TCPS2, please notify us upon completion of your project.

We wish you success with your research.

Yours sincerely,

Gail Wideman

Gail Wideman, Ph.D.
Vice-Chair, Interdisciplinary Committee on Ethics in Human Research

GW/th

copy: Supervisor – Dr. Orland Hoeber, Department of Computer Science

Director, Office of Research Services

Office of Research Services, Bruneau Centre for Research & Innovation   Page 1 of 1

Appendix B

Evaluation Documents

This appendix includes all the evaluation documents.

Informed Consent Form

Field Trials with Geovisual Analytics Software for Exploring Sonar Data

Researcher(s) Md Asikur Rahman,
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Dr. Orland Hoeber
Department of Computer Science
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You are invited to take part in a research project entitled *"Field Trials with Geovisual Analytics Software for Exploring Sonar Data"*.

This form is part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. It also describes your right to withdraw from the study at any time. In order to decide whether you wish to participate in this research study, you should understand enough about its risks and benefits to be able to make an informed decision. This is the informed consent process. Take time to read this carefully and to understand the information given to you. Please contact the researcher, Md Asikur Rahman, if you have any questions about the study or for more information not included here before you consent.

It is entirely up to you to decide whether to take part in this research. If you choose not to take part in this research or if you decide to withdraw from the research once it has started, there will be no negative consequences for you, now or in the future.

Introduction
My name is Md Asikur Rahman and I am a M.Sc. student in the Department of Computer Science. As part of my thesis, I am conducting research under the supervision of Dr. Orland Hoeber in the domain of geovisual analytics.

In the course of this research, we have developed a research prototype with the purpose of assisting analysts with their tasks of exploring geospatial sonar data based on their visual features. Our prototype software consists of two main visual components that provide coordinated filtering of the data: the visual space that includes clusters of the echogram slices, and the geographic space that includes the locations of these slices.

You have been selected to participate in this field trial due to your experience in analyzing sonar data.

Purpose of study:
The primary objective of this study is for the researchers to gain insight into how the prototype system that has been developed can be used in real-world problem solving and data exploration activities. We also wish to gain a deeper understanding of the types of problem solving and decision making activities that are being undertaken by the participants.

What you will do in this study:
In this study, you will be asked to use our system to analyze sonar data, exploring interesting patterns using clustered visual features and coordinated geovisualization. The data has been provided by the Marine Institute. After using our system to explore the sonar data, you will be asked to complete a questionnaire. A short interview will also be conducted in which we will ask your opinion on various aspects of our system and the types of data analysis you normally perform.

Your use of our system will be video recorded so that we can analyze your activities at a later date, and so that we can focus our attention on helping you to perform your data analysis tasks. The interview will be audio-recorded to ensure that we accurately capture your comments and discussion with the researcher.

Length of time:
The field trial is expected to take a total of 60 minutes.

Location:
The field trials will be conducted in the User Experience Lab (EN-2031A) within the Department of Computer Science.

Compensation:
For participating in this study you will receive $20.00 compensation for your time and effort.

Withdrawal from the study:
If you decide to withdraw from the research once it has started, there will be no negative consequences for you, now or in the future and; you will still receive the compensation. Any collected data, both paper and electronic, will be destroyed immediately if you decide to withdraw from this study. Your decision of whether or not to participate in this study will not be shared with Dr. Rose. The raw data will not be shared beyond our principal investigators in this project, and not even to our partners or external collaborators.

Possible benefits:
The primary benefit that you may find when participating in this study is the exploration of interesting patterns or aspects of the data using our proposed system that you had not previously been aware of. Further, your participation will provide us with valuable information regarding how you are able to perform data analysis tasks using our system. This will assist us validating our work as well as in the further development of our system.

Possible risks:
There are no risks or harms associated with this study beyond the normal use of a computer system.

Confidentiality and Storage of Data:
In order to maintain the privacy of your participation in this study, the data collected will be held strictly confidential by the researchers. Physical material will be kept in a secure on-campus location; electronic material will be stored on password-protected computer systems. Data will be kept for a minimum of five years, as per Memorial University policy on Integrity in Scholarly Research. When we decide to dispose of the data, all physical material will be shredded, and all digital media will be destroyed in accordance with University policy.

Anonymity:
Although we will communicate with you via email to coordinate your participation, your identity is not required during the actual study. You will not be required to write your name or any identifying information on the research questionnaires. Any identifying information will be kept separate from the details of your participation in the study. Any reporting of the outcomes of this research will exclude identifying information of the participants. The data itself will only be used by the researchers indicated in this consent form, and will not be shared in raw format with anyone.

Recording of Data:
Your use of the prototype system will be video recorded. However, the focus of the video recording will be on what you are doing with the system. As such, the video camera will be pointed at the computer screens, keyboard, and mouse. The audio portion of the recording will capture the discussions between yourself and the researcher. This video and audio recording will be captured and stored in electronic format only.

Data from the questionnaire will be collected on paper, and will subsequently be entered into an electronic format.

The interviews conducted after using the software will be audio-recorded, and will be stored in electronic format only.

Reporting of Results:
Results from this study will be published and shared with our key partner **Fisheries and Oceans Canada**. While the raw video and audio recordings will not be included in these reports, direct quotations and images from the video recording may be used. In these cases, we will ensure that any identifying information is removed.

Sharing of Results with Participants:
Once results of this study are published in any journal or conference, we will inform you of this. The results of this user study will be used for analysis and discussion in principal investigator's thesis as well as in the journal (Journal of Geomatics and Spatial Analysis). These may also be published in conferences and journals in the domain of visual analytics (Visual Analytics of Science and Technology, Transactions on Visualization and Computer Graphics, Information Visualization, etc.).

Questions:
You are welcome to ask questions at any time during your participation in this research. If you would like more information about this study, you may contact either of the researchers at the end of this document.

ICEHR Compliance:
The proposal for this research has been reviewed by the Interdisciplinary Committee on Ethics in Human Research and found to be in compliance with Memorial University's ethics policy. If you have ethical concerns about the research (such as the way you have been treated or your rights as a participant), you may contact the Chairperson of the ICEHR at [illegible] or by telephone at 709-864-2861.

Consent:
Your signature on this form means that:

- You have read the information about the research.
- You have been able to ask questions about this study.
- You are satisfied with the answers to all your questions.
- You understand what the study is about and what you will be doing.
- You understand that you are free to withdraw from the study at any time, without having to give a reason, and that doing so will not affect you now or in the future.
- You understand that your use of the software will be video recorded and your responses to the interview questions will be audio recorded.
- You understand that any data collected from you up to the point of your withdrawal will be destroyed.

If you sign this form, you do not give up your legal rights and do not release the researchers from their professional responsibilities.

Your signature:
I have read and understood what this study is about and appreciate the risks and benefits. I have had adequate time to think about this and had the opportunity to ask questions and my questions have been answered.

☐ I agree to participate in the research project understanding the risks and contributions of my participation, that my participation is voluntary, and that I may end my participation at any time.

A copy of this Informed Consent Form has been given to me for my records.

______________________________ ______________________________
Signature of participant Date

Researcher's Signature:
I have explained this study to the best of my ability. I invited questions and gave answers. I believe that the participant fully understands what is involved in being in the study, any potential risks of the study and that he or she has freely chosen to be in the study.

______________________________ ______________________________
Signature of Principal Investigator Date

Investigators:

Md Asikur Rahman M.Sc. Student Department of Computer Science Memorial University of Newfoundland Email: asikur.rahman@mun.ca	Dr. Orland Hoeber Assistant Professor Department of Computer Science Memorial University of Newfoundland Email: hoeber@mun.ca

Pre-Study Questionnaire Participant:_____

Please answer the following questions with regards to your background.

1. For how many years have you been involved in sonar data analysis?

2. Please list the different sonar data analysis software systems you have used.

3. What is your level of understanding of sonar data visualization (echograms)?
   (Not at all) (Very familiar)
   1 2 3 4 5

4. How familiar are you with virtual globes such as Google Earth, ArcGIS, or NASA Worldwind?
   (Not at all) (Very familiar)
   1 2 3 4 5

5. How familiar are you with systems that visually organize images such as Google Swirl?
   (Not at all) (Very familiar)
   1 2 3 4 5

6. How familiar are you with multiple coordinated views (systems that allow you to highlight data in one view, and then show you that same data in other connected views)?
   (Not at all) (Very familiar)
   1 2 3 4 5

Post-Study Questionnaire Participant:___

The following questions relate to your experience using our prototype system for exploring geospatial representations of sonar data. Your answers to the following questions will allow for a more accurate analysis of the data collected during this study.

INSTRUCTIONS: Please rate how strongly you agree or disagree with the following statements by circling the appropriate number.

The questions below deal with the visual organization of the echogram slices (top view).	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
The **visual organization** of the echogram slices enabled me to accomplish my data analysis tasks more quickly.	1	2	3	4	5
The **visual organization** of the echogram slices improved my data analysis performance.	1	2	3	4	5
The **visual organization** of the echogram slices increased my productivity.	1	2	3	4	5
The **visual organization** of the echogram slices enhanced my effectiveness in analyzing the sonar data.	1	2	3	4	5
The **visual organization** of the echogram slices made it easier for me to analyze the sonar data.	1	2	3	4	5
I found the **visual organization** of the echogram slices useful for analyzing the sonar data.	1	2	3	4	5

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
Learning to operate the **visual organization** of the echogram slices was easy for me.	1	2	3	4	5
I found it easy to get the **visual organization** of the echogram slices to do what I wanted it to do.	1	2	3	4	5
My interaction with the **visual organization** of the echogram slices was clear and understandable.	1	2	3	4	5
I found the **visual organization** of the echogram slices to be flexible to interact with.	1	2	3	4	5
It was easy for me to become skilful at using the **visual organization** of the echogram slices.	1	2	3	4	5
I found the **visual organization** of the echogram slices easy to use.	1	2	3	4	5

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
The **visual organization** of the echogram slices made sense to me.	1	2	3	4	5
I found it easy to understand why echogram slices were grouped together in the **visual organization**.	1	2	3	4	5
I was satisfied with the **visual organization** of the echogram slices.	1	2	3	4	5

The questions below deal with the geovisual organization of the echogram slices (bottom view).	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
The **geovisual organization** of the echogram slices enabled me to accomplish my data analysis tasks more quickly.	1	2	3	4	5
The **geovisual organization** of the echogram slices improved my data analysis performance.	1	2	3	4	5
The **geovisual organization** of the echogram slices increased my productivity.	1	2	3	4	5
The **geovisual organization** of the echogram slices enhanced my effectiveness in analyzing the sonar data.	1	2	3	4	5
The **geovisual organization** of the echogram slices made it easier for me to analyze the sonar data.	1	2	3	4	5
I found the **geovisual organization** of the echogram slices useful for analyzing the sonar data.	1	2	3	4	5

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
Learning to operate the **geovisual organization** of the echogram slices was easy for me.	1	2	3	4	5
I found it easy to get the **geovisual organization** of the echogram slices to do what I wanted it to do.	1	2	3	4	5
My interaction with the **geovisual organization** of the echogram slices was clear and understandable.	1	2	3	4	5
I found the **geovisual organization** of the echogram slices to be flexible to interact with.	1	2	3	4	5
It was easy for me to become skilful at using the **geovisual organization** of the echogram slices.	1	2	3	4	5
I found the **geovisual organization** of the echogram slices easy to use.	1	2	3	4	5

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
The **geovisual organization** of the echogram slices made sense to me.	1	2	3	4	5
I found it easy to understand the order of the echogram slices within the **geovisual organization.**	1	2	3	4	5
I was satisfied with the **geovisual organization** of the echogram slices.	1	2	3	4	5

The questions below deal with the coordinated interaction between the two views of the data.	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
When zooming in the visual space, the **coordinated interaction** with the geographic space improved my understanding of the data.	1	2	3	4	5
When zooming in the geographic space, the **coordinated interaction** with the visual space improved my understanding of the data.	1	2	3	4	5
The **coordinated interaction** between the visual space and the geographic space enhanced my understanding of the relationships between the echogram slices.	1	2	3	4	5

The questions below deal with the ability to highlight individual echogram slices from the visual organization.	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
Highlighting echogram slices enabled me to accomplish my data analysis tasks more quickly.	1	2	3	4	5
Highlighting echogram slices improved my data analysis performance.	1	2	3	4	5
Highlighting echogram slices increased my productivity.	1	2	3	4	5
Highlighting echogram slices enhanced my effectiveness in analyzing the sonar data.	1	2	3	4	5
Highlighting echogram slices made it easier for me to analyze the sonar data.	1	2	3	4	5
I found the **highlighting of echogram slices** useful for analyzing the sonar data.	1	2	3	4	5

The questions below deal with the ability to highlight individual echogram slices from the geovisual organization.	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
Highlighting echogram slice locations enabled me to accomplish my data analysis tasks more quickly.	1	2	3	4	5
Highlighting echogram slice locations improved my data analysis performance.	1	2	3	4	5
Highlighting echogram slice locations increased my productivity.	1	2	3	4	5
Highlighting echogram slice locations enhanced my effectiveness in analyzing the sonar data.	1	2	3	4	5
Highlighting echogram slice locations made it easier for me to analyze the sonar data.	1	2	3	4	5
I found the **highlighting echogram slice locations** useful for analyzing the sonar data.	1	2	3	4	5

The questions below deal with the ability to merge a group of echogram slices back into a subset of the echogram.	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
The ability to **merge echogram slices** enabled me to accomplish my data analysis tasks more quickly.	1	2	3	4	5
The ability to **merge echogram slices** improved my data analysis performance.	1	2	3	4	5
The ability to **merge echogram slices** increased my productivity.	1	2	3	4	5
The ability to **merge echogram slices** enhanced my effectiveness in analyzing the sonar data.	1	2	3	4	5
The ability to **merge echogram slices** made it easier for me to analyze the sonar data.	1	2	3	4	5
I found the ability to **merge echogram slices** useful for analyzing the sonar data.	1	2	3	4	5

Thank you for your participation!

Interview Questions:

1. Can you tell us what you liked about the visual organization of the echogram slices? Was there anything that you did not like?
2. Can you tell us what you liked about the geographic view? Was there anything that you did not like?
3. Did you like the coordinated interaction between visual space and geographic space? Was there anything that you did not like about this?
4. Did you like the highlighting of an individual echogram slice and its corresponding geographic location? Was there anything that you did not like about this?
5. Did you like the highlighting of an echogram slice location and its corresponding echogram slice? Was there anything that you did not like about this?
6. Did you like the ability to merge the echogram slices? Was there anything that you did not like about this?
7. Do you think that, GVFO System supports knowledge discovery activities, and a more comprehensive analysis of the data across distant geographic ranges than traditional echogram analysis approaches?
8. Did you experience any problems, difficulties, or confusion while using the prototype software? Please explain.
9. Do you have any comments or suggestions about how we can improve the prototype software?